Assessing Airport Noise, Demand for Quietness and Land-Structure Substitution: Three Applications of the Hedonic Model in Switzerland

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To my mother
and in memory of my father.

Contents

Abstract

This dissertation collects three essays on the hedonic modelling of housing prices, location attributes and environmental amenities – or lack thereof.

The first essay applies spatial econometric techniques to measure the impact of airport noise on the price of single-family homes in the Zurich Airport area. We exploit a large database of geo-referenced noise measurements to investigate the reaction of house prices to different noise metrics. The particular institutional setting of Zurich Airport, with a changing pattern of runway configurations allows to distinguish the impact of noise at different times of the day. The use of neighborhood fixed-effects is compared to the results given by a costlier modelling strategy involving a rich set of location descriptors. We document the impact of airport noise on housing prices. In the base model specification, the Noise Discount Index, i.e. the percentage depreciation per dB of aircraft noise, is 0.97%. Typical discounts are in the range of −2% to −8%. The results are similar to comparable Swiss and international studies on the impact of aircraft noise on residential property prices. From a methodological point of view, we show that accounting for the spatiality of the data has little effect on the results.

In the second essay we estimate the willingness to pay for housing attributes of single-family home owners located in the greater Zurich area. A revealed-preferences approach is used, in which a structural hedonic model is identified and estimated. Our approach explicitly accounts for the heterogeneity of preferences of the owner-occupiers. Again, we use the GIS to match the data describing the housing characteristics and the attributes of the location to the socioeconomic traits of the owners. We perform a nonparametric estimation of the hedonic model that allows us to recover the preference parameters. We measure the impact of income differences on the willingness to pay for five major characteristics, i.e. travel time to the city center, size and age of the housing unit, lot size and proximity to a major environmental amenity, the Lake of Zurich. We show that the willingness to pay for the environmental amenity and for centrality is highly income elastic, while the demand for the lot size and for the house surface is not. We put the model in the context of the new urban economic literature which studies the importance of amenities for the location decision of households in cities.

In the last part of the dissertation, we touch on another typical urban economics topic – the elasticity of substitution between capital and land. This concept is key in understanding some important phenomena like urban sprawl or urban density. Combining two new rich data sets on disaggregated land and house transactions, we propose one of the first estimates of this elasticity for a non-U.S. metropolitan region. For the region of Zurich we find an elasticity of substitution of 0.6 and an own-price elasticity of the demand for land of −0.5. These relatively low estimates imply that a policy aiming at restricting the supply of open spaces and limiting the availability of unimproved land may have a large impact on house prices.

JEL-Classification: Q53, Q51, R31, L93, C21
Keywords: hedonic pricing, environmental valuation, aircraft noise, urban economics, spatial econometrics, capital-land substitution, GIS.

Résumé

Cette thèse de doctorat rassemble trois études sur l'évaluation des prix des logements par la méthode hédoniste. Nous y examinons la valorisation des attributs liés à la situation, en particulier celle des aménités environnementales.

La première étude applique des techniques d'économétrie spatiale pour mesurer l'impact du bruit des avions sur le prix des villas dans la région de l'aéroport de Zurich. L'accès à une base de données géoréférencées des nuisances sonores et la configuration changeante des pistes durant la journée nous permet d'étudier la réaction des prix à différents aspects du bruit. Une modélisation simple par « fixed-effects » est comparée aux résultats d'une stratégie plus coûteuse, impliquant plusieurs variables décrivant la situation. Nous documentons un impact significatif du bruit sur le prix des villas, avec une dépréciation de 0.97% par décibel supplémentaire. Pour une villa typique ces moins-values correspondent à entre -2% et -8% de la valeur d'achat. Ces résultats sont semblables à ceux documentés par d'autres études suisses et internationales. D'un point de vue méthodologique, nous montrons que la prise en compte de la spatialité des données n'a que peu d'effet sur les résultats.

Dans le deuxième volet de la thèse, nous estimons par la méthode des préférences révélées la disposition à payer pour les principales caractéristiques de villas. Notre approche tient compte explicitement de l'hétérogénéité des préférences des propriétaires. Nous utilisons à nouveau le GIS pour relier les données décrivant les caractéristiques des logements à celles décrivant la situation et les traits socio-économiques des propriétaires. Nous effectuons une évaluation non paramétrique du modèle hédoniste qui nous permet d'estimer les paramètres de préférence. Nous mesurons l'impact des différences de revenu sur la disposition à payer pour cinq caractéristiques fondamentales des logements : la taille et l'âge du bâtiment, la surface de la parcelle, le temps de parcours moyen vers le centre ville et la proximité de la villa par rapport à l'aménité environnementale majeure, à savoir le Lac de Zurich. Nous montrons que la disposition à payer pour l'aménité environnementale et pour la centralité est fortement élastique par rapport au revenu. En revanche l'élasticité-revenu pour la grandeur de la parcelle et la taille du logement est basse. Le modèle est ensuite placé dans le contexte de la recherche en économie urbaine qui étudie l'importance des aménités environnementales pour le choix de localisation des ménages.

Dans la dernière partie, nous reprenons un autre « classique » de l'économie urbaine – l'élasticité de substitution entre le capital et le sol. Ce concept est indispensable à une bonne compréhension de phénomènes urbains importants comme l'étalement des villes et l'évolution de la densité urbaine. Nous relions deux bases de données – l'une contenant l'ensembles des transactions de terrain à bâtir dans le canton de Zurich, l'autre celle des transactions de villas – afin de permettre l'une des premières estimations de l'élasticité de substitution pour une agglomération européenne. Nous estimons une élasticité de substitution de 0.6 et une élasticité de la demande par rapport au prix du terrain de -0.5. Ces élasticités relativement basses impliquent qu'une politique visant à limiter la disponibilité de terrain à bâtir pourrait avoir un fort impact sur les prix des logements.

Classification JEL : Q53, Q51, R31, L93, C21
Mots clés : modèle hédonique, évaluation environnementale, bruit, économie urbaine, statistique spatiale, élasticité de substitution, prix des terrains, mitage urbain, GIS.

Zusammenfassung

Diese Dissertation umfasst drei Beiträge zum Thema der hedonischen Modellierung von Immobilienmärkten. Die Schätzung der Zahlungsbereitschaft der Haushalte für die Eigenschaften einer Wohnlage und die damit verbundenen Umweltfaktoren stehen im Zentrum der Arbeit.

Der erste Teil der Dissertation wendet Methoden der räumlichen Statistik an, um die Wirkung von Fluglärm auf die Preise von Einfamilienhäusern (EFH) im Einzugsgebiet des Flughafens Zürich zu messen. Dank einer umfassenden Datenbasis von georeferenzierten Lärmmessungen werden verschiedene Dimensionen der Lärmbelastung berücksichtigt. Die besondere Organisation des Flugbetriebs in Zürich, mit tageszeitlich variierenden An- und Abflugrouten, ermöglicht es, eine Analyse der zeitabhängigen Wirkung des Fluglärms durchzuführen. Es werden ferner verschiedene Spezifikationen des hedonischen Modells gegenübergestellt. Insbesondere werden die Ergebnisse eines "Fixed-Effect"-Modells mit jenen einer umfassenden Spezifikation verglichen, die zahlreiche Lagevariablen beinhaltet.
Der Beitrag belegt einen signifikanten Einfluss der Fluglärmbelastung auf die EFH-Preise. Im bevorzugtem Modell bewirkt ein zusätzliches Dezibel Tageslärmbelastung eine Preisminderung von 0.97%. Typische Preisminderungen betragen -2% bis -8%. Dies entspricht den von der schweizerischen und der internationalen Literatur ermittelten Werten. Es zeigt sich zudem, dass räumliche Effekte vernachlässigbar sind.

Im zweiten Teil wird die Zahlungsbereitschaft für die Merkmale von Einfamilienhäusern – insbesondere ihrer Lage – im Kanton Zürich untersucht. Wir spezifizieren und schätzen ein strukturelles hedonisches Modell, das die Heterogenität der Präferenzen der Eigentümer explizit berücksichtigt. Aus diesem Grund werden die sozioökonomischen Merkmale der Eigentümer/Haushalte mit den Eigenschaften der Liegenschaften verbunden. Die Analyse wendet eine neuere nicht-parametrische Schätzmethode an, um die Zahlungsbereitschaft nach den wichtigsten strukturel-

len Merkmalen der Liegenschaften (Hausgrösse, Grundstücksfläche und Alter) und der Lage (Zentralität, Nähe zum See) zu bestimmen. Wir zeigen, dass die Bewertung der Lage- und Umweltmerkmale stark einkommensabhängig ist, wobei jene der strukturellen Merkmale eine wesentlich tiefere Einkommenselastizität aufweist. Wir kommentieren diese Ergebnisse im Lichte der neuen Stadtökonomie, welche die Relevanz der Umweltqualität für die Wahl des Wohnortes betont.

Schliesslich wird im dritten Teil ein weiteres typisches Thema der Stadtökonomie behandelt, die Substitutionselastizität zwischen Kapital und Land bei der Produktion von Wohnraum. Ein gutes Verständnis dieser Substitutionsbeziehung ist für den nachhaltigen Umgang mit der knappen Ressource "Boden" unabdingbar. Die Substitutionselastizität ist für das Verständnis wichtiger urbaner Phänomenen wie die Zersiedlung und die Entwicklung der städtischen Dichte zentral. Wir verknüpfen zwei umfassende Datensätze über die Boden- und Eigenheimtransaktionen im Kanton Zürich, um eine der ersten Schätzungen dieser Grössen für eine Metropolitanregion ausserhalb der Vereinigten Staaten durchzuführen. Für den Kanton Zürich wird eine Substitutionselastizität von 0.6 und eine Preiselastizität der Bodennachfrage von -0.5 gemessen. Diese relativ tiefen Werte bedeuten, dass eine Politik, welche die Begrenzung von überbaubaren Flächen eine grössere Wirkung auf die Wohn- und Immobilienpreise ausüben würde.

JEL-Classification: Q53, Q51, R31, L93, C21
Schlüsselwörter: hedonisches Modell, Umweltbewertung, räumliche Statistik, Fluglärm, GIS, Substitutionselastizität, Stadtökonomie.

Chapter 1

Introduction

According to folk wisdom, an economist is someone who knows the price of everything and the value of nothing. Of course, this judgment is a gross exaggeration: many goods do not trade on well-organised markets, inferring their price – not to speak of their value – is for most economists a cumbersome undertaking. In this work we use a simple technique, hedonic modelling, to evaluate some important environmental goods that shape the daily life of many consumers in highly mobile societies. Some of these goods, as the quietness from aircraft noise, are classical examples of environmental externalities. They do not trade on a specific market as their property rights are not fully assigned. Other goods or environmental characteristics, like land plots associated with the proximity to an environmental amenity, do trade on markets. However, the amenity we would like to evaluate is bundled with the other characteristics of the traded good. It is just one of the many dimensions of a differentiated good.

This is where the hedonic model of property market comes into play. The property market is a complementary market where environmental quality is implicitly traded. We can infer its price and market valuation by disentangling its specific effect from the other characteristics of the traded properties.[1] Hence, the hedonic model works within the framework of the revealed preferences approach for valuing the environment. It uses information on what people do, not what they say.[2]

[1]The labor market is another market where the implicit valuation of environmental qualities can be inferred.

[2]On the revealed preferences approach, see the excellent book by Bockstael and McConnell (2007).

The hedonic model assumes that there is a schedule of prices for each of the characteristics bundled in the differentiated product, i.e. houses. Under suitable conditions, this schedule can be estimated. The first difficulty of this estimation arises from the fact that each house differ from the another along many dimensions. It is then of some importance to be able to precisely describe the relevant characteristics. The recent availability of geographic information systems (GIS) and georeferenced data has greatly improved our ability to thoroughly describe the attributes of a location. The essays in this dissertation make a heavy use of georefrenced data.

Differences between houses or locations may still be imperfectly measured. It then becomes difficult to isolate the effects of a particular amenity on the house prices. This issue can be addressed with the use of specific statistical techniques, known as spatial statistics or spatial analysis. Again, the availability of geocoded data allows us to use these promising techniques, which are still in development. An application is found in the first essay, where we investigate the importance of spatial correlation for the evaluation of airport noise.

Another difficulty of the hedonic valuation of environmental goods with real estate data is the sorting issue. Typically, amenities are not distributed randomly across houses and locations. Households move to houses or locations endowed with characteristics that match their preferences. When we use observed price differentials to infer the value that consumers put in general on a particular amenity, we must be aware that sorting drives a wedge between the valuation of the population at large and the one of the households most willing (or able) to enjoy the amenity. The gap will be particulary large whenever there is a large heterogeneity of tastes and/or income between the two groups. To put it bluntly: if in the land of the blind the one-eyed man is king, quietness is cheap in the country of the deaf. In the second essay we go into some detail in order to treat this sorting/heterogeneity issue when we evaluate the willingness to pay for the housing and location characteristics of single-family homes in the Canton of Zurich.

The third essay of the dissertation uses hedonic modelling to address an aspect of what has been dubbed "the sprawl" of the agglomerations into the countryside. In Switzerland, as in many other countries, urban dwellers have been enjoying access to better and larger houses. This has been done at the cost of sacrificing open spaces. Raising urban density is often advocated as a sustainable way to satisfy the increasing demand for new housing units. The capacity of the housing market to react to a "shortage" of land is central to this debate. Again, we use hedonic modelling to address this question empirically.

If anything, economists know the the value of good data. The scale and scope of statistical analysis often distinguishes economics from its competitors. This is evident in the subfield of urban economics, where the focus on empirical work stands in stark contrast with the mainly normative, top-down approach of urban planners. Within the real estate industry, widespread access to databases on property transactions has spurred the use of statistical valuation methods. This has had repercussions on other fields, too. In Switzerland for example, it has played a major role in the recent decision of the Swiss Federal Supreme Court to allow the use of the hedonic model presented in the part I in the noise compensation litigations at Zurich Airport. To the best of our knowledge, this case represents potentially one of the single largest settlements involving the use of hedonic valuation of environmental damage, as it is likely to involve the payment of around 1 billion Swiss Francs. It was a deep satisfaction for an applied economist to participate in this project.

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I also thank all those who have in a way or another contributed to initiate this project, have encouraged me to continue, or have helped finishing it. In particular, I am grateful to Andreas Bröhl, Fabien Cerutti, Ivan Farron, Melanie Grütter, Gion-Reto Hassler, Alice Hollenstein and Jörn Schellenberg. Finally, I thank Rodolfo Biagi, Francisco Canaro and Edgardo Donato for their faithful company over the years.

Part I

The Impact of Airport Noise on Housing Prices

Chapter 2

Spatial Hedonic Modelling

2.1 Introduction

The impact of airport proximity on neighboring communities is a hotly debated topic. The positive aspects of proximity are related to the provision of communication links and to the direct economic importance of large airports. The downside of proximity are the adverse environmental effects primarily associated with aircraft noise. The growing interdependence and global connectivity of modern economies has increased the economic importance of air travel. On the other hand, environmental quality tends to be a superior good – as per capita income rise, the social demand for environmental quality increases more than proportionally. It is thus fair to say that airport noise is bound to fuel ongoing public debate.

The recent story of Zurich Airport is in this regard exemplary. Until the year 2000 the use of German airspace for approaching and leaving Zurich airport had been governed by a bilateral agreement between Switzerland and Germany. The agreement was terminated by Germany in 2000, forcing the Swiss authorities to set out new landing procedures. As a result, the number of residents subject to aircraft noise increased significantly. Under the Swiss noise protection law these residents may be entitled to compensation and over 19,000 have filed a claim. This has drastically increased the public awareness for the evaluation of the cost of noise. Specifically, the use of the hedonic method for the scope of evaluation and compensation has been proposed. Recently, the Federal Supreme Court of Switzerland has decided that a version of the model presented here can be used in the noise compensation litigations at Zurich Airport (Schweizerisches Bundesgericht, 2008).[1]

As with other nuisances, like air pollution or the proximity to landfill sites, the hedonic framework has been applied to measure the capitalization of airport noise in house prices.[2] The basic economic rationale is the following: although the market for quietness is missing, a complementary market exists wherein individuals reveal their willingness to pay to avoid different levels of aircraft noise exposure. In the recent empirical economic literature on noise valuation surveyed in Nelson (2008), the question of the value placed by consumers on tranquillity has been typically estimated by regressing the house price (or rent) on selected structural and location characteristics.[3]

The hedonic regression corresponds to the first of the two-step methodology proposed by Rosen's seminal paper (Rosen, 1974). As shown by Ekeland, Heckman and Nesheim (2002) the implicit price of noise does not readily identify the marginal valuation of consumers for quietness, bar restrictive conditions. The correct way to identify the willingness to pay for the characteristics of a differentiated good is an open subject of research and the present work does not attempt identification.[4] Nonetheless, the measurement of the implicit price for noise is of the foremost interest whenever – as with the case at hand – the compensation of neighbors is an issue. Indeed, the final compensation awarded by the courts is likely to be related to the loss in market value of the assets more than to the loss of economic rents associated to them.

This essay aims to establish the following contributions to the hedonic noise valuation literature:

1 Spatial statistics: Until recently, hedonic regression were simply estimated

[1]Many conditions have to be met in order to receive compensation. Residents must suffer a severe depreciation of the property, meaning a noise impact of at least 10% of the value. Only buyers of houses in areas where the noise increase was "not foreseeable" at the time of the transaction are entitled to compensation. The total sum of the compensations is estimated by Zurich Airport at slightly less than 1 billion Swiss francs.

[2]See Palmquist (2006) for an overview of the use of hedonic valuation models. For other approaches to the valuation of airport, as contingent valuation or valuation based on happiness surveys, see Navrud (2002) and van Praag and Baarsma (2005), respectively.

[3]See also Salvi (2001) for a Swiss contribution to the valuation of traffic noise.

[4]For contributions, see Bajari and Kahn (2002); Bayer, McMillan and Ruben (2002), and the second part of the present dissertation, among others.

by ordinary least squares (OLS). Thanks to advances in spatial econometrics and in statistical software, there is a rising awareness of the potential importance of spatial effects in hedonic modelling.[5] However, most contributions have not considered spatial specifications issues.[6] Following the recommendations in Florax, Folmer and Rey (2003), we carefully test and account for the presence of spatial externalities. We then compare the results of different spatial specifications and judge the added-value of spatial statistics.

2 Disaggregate noise exposure data: The perceived noise intensity can vary greatly, even for apparently similar sites located at the same distance from the runways. Many factors influence the noise perceived at a given location, as, for example, the sound diffraction of the terrain, the availability of instrument approach procedures or the weather. This essay uses a proprietary aircraft noise model provided by the *Swiss Federal Laboratories for Materials Testing and Research* (EMPA). The EMPA model was specifically calibrated and validated for use at Zurich airport. While many contributions have explicitly used aircraft noise data (as opposed to cruder measures of distance to the runways or flight paths), few have taken into account truly disaggregate noise data. Even the relatively recent contribution of McMillen (2004), as well as the aforementioned study by Cohen and Coughlin (2006), have only access to a dummy variable indicating whether the transaction is located inside a given noise boundary. Moreover, our disaggregate data allow to distinguish between the impact of noise exposure depending on the time of the day.

3 GIS coverage: Our analysis uses an extensive geodatabase. In addition to several accessibility variables, the database covers additional nuisances as road traffic noise. When measuring the impact of aircraft noise on property prices it is important to have access to good control variables because location

[5]In their survey of the impact of landscape amenities on property prices, Waltert and Schläpfer (2007) identify seven studies which controlled for spatial autocorrelation, all of them published between 2000 and 2005.

[6]In the noise evaluation literature, Cohen and Coughlin (2006) are an exception as they explicitly consider the specification and estimation of a spatial model.

variables are correlated. A special effort is devoted here to the modelling of terrain characteristics as, for example, the presence of a scenic view. As a by-product of the analysis, we assess the added value of using precise geographical information as opposed to a simpler specification.

4 Housing transactions: For around 4'000 arm's-length transactions, actual selling prices were gathered, along with detailed structural characteristics. For each transaction an unusual high number of quality attributes were collected.

The organization of the remainder of this essay is the following. After a motivation of the use of spatial econometric techniques, we gives a short overview of the spatial model most likely to suit the case at hand. In Chapter 3 we describe the single-family housing transaction data used in the empirical study. We also give an account of the noise data. We then perform an explorative spatial analysis of the data. On the basis of these results, a spatial setup is chosen. Finally, the results of both the spatial and non-spatial estimations are presented and discussed.

2.2 Spatial Modelling

2.2.1 Why Use Spatial Econometrics?

Spatial econometrics provides the researcher with a wide array of models and estimation techniques dealing with various kinds of spatial dependence. The correct representation of spatial externalities justifies – and indeed often requires – the specification and estimation of spatial econometric models (Anselin, 2003). Its use in real estate economics is growing and has been surveyed by Dubin, Pace and Thibodeau (1999). In spatial econometrics, dependencies that may arise through the interaction between neighboring locations are dealt with techniques similar to, but distinct from, those used in standard econometrics when dealing with issues of time dependence, heteroskedasticity or simultaneity.

What is the intuition behind our use of spatial econometric techniques? In the case of the estimation of an hedonic regression in a real estate context, it is conceivable that houses heavily exposed to aircraft noise will be located in less affluent neighborhoods with lower building standards. If the covariates controlling for building quality and location in the hedonic regression are incomplete, some of the negative impact attributed to aircraft noise is in fact spurious. It should be related to the lower quality of the building or location, not to the noise exposure. In general, the "correct" specification of the hedonic regression may require the gathering of a large amount of data, some of them – e.g. variables describing the architectural style, or the presence of specific local amenities – may not usually be available to the researcher. This misspecification could entice a correlation between the estimation errors of neighboring observations subject to the influence of the same unobserved location characteristics. This kind of spatial dependence is known as *spatial autocorrelation* in the spatial econometrics literature. Ignoring this dependence is akin to the neglect of the time ordering of temporal series. As in this latter case, the OLS estimator is not efficient and the covariance matrix of the estimated parameters is not valid, even asymptotically.

2.2.2 How to Model Spatial Externalities

Consider first the simple linear hedonic model

$$y_i = x_i'\beta + \varepsilon_i, i = 1, \ldots, N \tag{2.1}$$

where y_i is the price of the i-th observation (corresponding to a housing unit i), x_i is a K by 1 vector of housing characteristics associated with the K by 1 parameter vector β, and ε_i is an element of a sequence of random error variables with $E[\varepsilon_i] = 0$ and N by N variance-covariance matrix $\Omega_\varepsilon = E[\varepsilon\varepsilon']$. A spatial ordering specifies which observations mutually interact, i.e. which element of Ω_ε is non-zero depending on the relative location $|i - j|$. To this purpose a N by N spatial weighting matrix W is introduced which relates the realization of the random variable ε_i to the values at neighboring locations. Some structure has to be imposed a priori on this matrix as we have N observations to estimate $N(N-1)/2$ coefficients. In general, $w_{i,j} \neq 0$ for neighboring observations, and $w_{i,j} = 0$ otherwise.[7] The most commonly used spatial process specification is the

[7] Diagonal elements w_{ii} are set by convention to 0. Typically, the spatial weight matrix is row-standardized such that $\sum_{j=1}^{N} w_{ij} = 1$, $i = 1, \ldots, N$. With row-standardized matrices, weighting

autoregressive model (SAR). It is given as

$$\varepsilon_i = \lambda \sum\nolimits_{j \neq i} w_{ij} \varepsilon_j + u_i \tag{2.2}$$

where λ is the spatial autoregressive parameter, u_i is an element of a sequence of *i.i.d.* random error variables with $u_i \sim (0, \sigma_u^2)$. For this spatial process the corresponding variance-covariance matrix is

$$\Omega_\varepsilon = \sigma_u^2 \left[(I - \lambda W)^{-1} (I - \lambda W)^{-1\prime} \right]. \tag{2.3}$$

As shown in Anselin (2003), with this specification every location is correlated with every other location, but closer locations more so. Thus, the SAR model is an example of a model with "global spillovers". A frequently used, alternative spatial specification is the spatial moving average (SMA), where (2.2) is replaced by

$$\varepsilon_i = u_i - \rho \sum\nolimits_{j \neq i} w_{ij} u_j. \tag{2.4}$$

Here the error term ε_i is influenced by directly interacting locations as given by the non-zero elements of W. The variance-covariance matrix of the SMA is

$$\Omega_\varepsilon = \sigma_u^2 [I + \rho(W + W') + \rho^2 W W']. \tag{2.5}$$

Suppose the weighting matrix W is defined as a first order contiguity matrix, where $w_{ij} = 1$ whenever the observations i, j are contiguous (according to some metric), or else $w_{ij} = 0$. Two observations l, m are second-order neighbors, if there exists some observation r with $w_{lr} = 1$, $w_{rm} = 1$, $w_{lm} = 0$. The typical off-diagonal element of Ω_ε is non-zero only whenever the corresponding elements in W (or W') and WW' are non-zero. Such elements consist only of first and second-order neighbors. Higher-order neighbors are absent from Ω_ε, and it is in this sense that the SMA model can be considered as representing spatial dependence with "local spillovers".

Spatial dependence could also be channelled through the regressors WX or through a lagged dependent variable Wy. For example, practitioners in the prop-

operations can be interpreted as an average of the neighboring values. However, even under these restriction several alternative weighting schemes are still possible.

erty market often argue that due to the lack of transparency and liquidity of the residential real estate market, sellers and buyers rely on transaction prices of "comparables" as their only source of price information. This may entice a spatial correlation between surrounding housing prices. Hence, a given house price would not only be related to the physical characteristics of the house and its location. It may thus tempting to add the spatially weighted average of the surrounding prices Wy to the model, i.e.

$$y = \rho Wy + X\beta + \varepsilon, \tag{2.6}$$

where ρ is the spatial lag parameter and $\varepsilon \sim N(0, \sigma^2 I)$. This so-called "spatial lag model" can be rewritten as

$$y = (I - \rho W)^{-1} X\beta + (I - \rho W)^{-1}\varepsilon. \tag{2.7}$$

In this case the dependent variable at a given location y_i is partly determined by the error terms at all locations (ANSELIN, 2003). This generates an endogeneity which requires special estimation techniques, such as spatial versions of the Generalized Method of Moments (KELEJIAN and PRUCHA, 1999).

2.2.3 Spatial Specification Searches

In the absence of guidance by theory, the choice of spatial model is largely an empirical question. Recently, FLORAX, FOLMER and REY (2003) argue in favor of an approach based on a battery of specification tests performed on the OLS residuals of a hedonic regression. The tests are locally robust variations of the classical Lagrange Multiplier test. The first, denoted LM^*_λ, tests for the presence of a spatial autoregressive error (SAR) process, as in equation (2.2)

$$LM^*_\lambda = \frac{\left(\hat{\varepsilon}' W \hat{\varepsilon} / \hat{\sigma}^2 - T\,(NJ)^{-1}\,\hat{\varepsilon}' W y \hat{\sigma}^2\right)^2}{T\,[1 - T\,(NJ)]^{-1}} \tag{2.8}$$

with

$$J = \frac{1}{N\hat{\sigma}^2}\left[\left(WX\hat{\beta}\right)' M \left(WX\hat{\beta}\right) + T\hat{\sigma}^2\right], \tag{2.9}$$

where $\hat{\varepsilon}$ is the vector of OLS residuals, T is the trace of the matrix $(W' + W)W$ and $M = I - X'(X'X)^{-1}X'$. Under the null of no spatial autocorrelation, this statistic is $\chi^2(1)$-distributed. Alternatively, the test for a spatially lagged dependent variable as in equation 2.6, denoted LM^*_ρ is defined

$$LM^*_\rho = \frac{\left(\hat{\varepsilon}'Wy - \hat{\varepsilon}'W\hat{\varepsilon}/\hat{\sigma}^2\right)^2}{NJ - T}. \tag{2.10}$$

Under the null of no spatial dependence, this statistic is $\chi^2(1)$-distributed. Their testing strategy – dubbed "hybrid approach" – can be summarised as follows:

1. Estimate the hedonic regression (2.1) with OLS.
2. Test the hypothesis of no spatial dependence due to an omitted spatial lag or to spatially autoregressive errors, using LM^*_ρ and LM^*_λ, respectively.
3. If both tests are not significant, the initial estimates from step 1 are used as the final specification. Otherwise proceed to step 4.
4. If only one test is significant, estimate the model accordingly. If both tests are significant, estimate the specification pointed to by the more significant of the two robust tests.

So, if LM^*_λ is less significant than LM^*_ρ, a specification with a spatial AR process and without lagged dependent variable should be fitted. In the Monte-Carlo simulation reported in Florax, Folmer and Rey (2003), this hybrid approach fares well when compared to more complex alternative modelling strategies. It is also adopted in the present work.

Chapter 3

Valuation of Aircraft Noise at Zurich Airport

3.1 Data

3.1.1 EMPA Aircraft Noise Data

Zurich Airport is Switzerland's largest airport with 270'000 take-offs and landings per year (Flughafen Zürich AG, 2008). The *Swiss Federal Laboratories for Materials Testing and Research* (EMPA) have provided model-based aircraft noise data in the vicinity of Zurich airport area on a regular basis. As with other aircraft noise models, the EMPA model produces noise exposure contours based on terrain, effective radar flight track information and aircraft noise profile. In addition, further variables influencing the local acoustic environment are explicitly modelled, as, for example, the effect of the prevalent winds.[1] The EMPA data used in this study consist of average noise immissions measured according to different variants of the L_{eq} (noise equivalence level) metric. The measures are available over varying time intervals, the hourly interval being the shortest. The noise contours are laid on a 100m-by-100m square lattice grid. Each pixel represents the average noise immission affecting a given location during a specific time interval over the course of one year. For each location and for each year dating back to 1987, a set of 24 hourly average noise levels is available. The aircraft data corresponding to

[1] See Thomann, Bütikofer and Krebs (2004) for a detailed description of the EMPA aircraft noise model.

the sale year are matched to the housing transactions.[2]

The L_{eq} metric maps noise events into an equivalent continuous, A-weighted sound pressure level, measured in decibel (dB). A-weighting adjusts sound pressure towards the frequency range of human hearing. The L_{eq} metric corresponds to the steady sound level that, over a specified period of time would produce the same energy equivalence as the fluctuating sound level actually occurring.

L_{eq} is routinely used in the measurement of noise exposure, although its justification as a single-number descriptor of aircraft noise is subject to considerable debate (Jones, 1997). The debate pertains in particular to the time span over which the aggregation should be performed. Averaging over many hours smoothes out peaks in the noise exposure. At Zurich Airport runaway patterns vary considerably over the course of the day. Some locations are affected only during the evening hours, others only in the morning. For these locations, averaging over daytime may result in low overall L_{eq} values, although the residents are exposed to significant noise during peak hours. Home-owners may perceive the location as noisy, irrespective of the low average noise measures. To further investigate this issue we consider three distinct noise metrics:

- L_{eq} 16h: The equivalent continuous noise level measured over 16 daytime hours, starting at 6am and ending at 10pm. This metric measures the "mean" noise level at a given location. It is considered in the Swiss noise abatement legislation.

- L_{eq} peak: The highest 1-hour L_{eq} measured during daytime (i.e. from 6am to 10pm), in excess of L_{eq} 16h. This measure is meant to capture the peak-level, daytime noise which might be "averaged out" by the L_{eq} measure.

- L_{eq} evening: The average noise level measured between 9pm and 11pm. This metric captures noise exposure during the sensitive evening hours, when most residents are at home and try to get to sleep.

The three metrics represent different "shades" of aircraft noise. Due to the changing runway patterns and flying paths at Zurich Airport, the metrics are

[2]Only noise exposures over 50 dB(A) are considered here. Exposures under this cut-off are too low to be reliably estimated by the EMPA model (G. Thomann, pers. comm.). We put these observations on the same level as the lack of noise.

largely uncorrelated.[3] Figure 3.1 traces out the noise contours with exposure over 50dB for the three different metrics. Notice that we do not consider night-time and early morning exposure. Zurich airport has the strictest night flying rules in

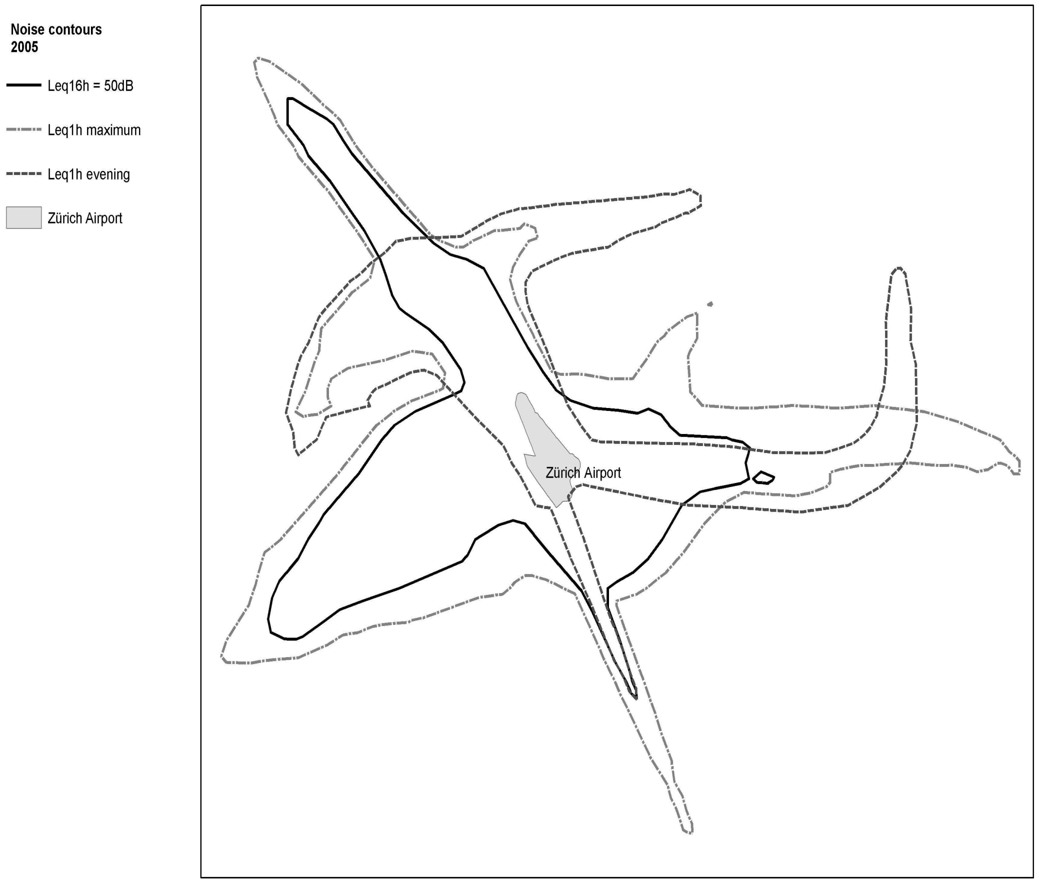


Figure 3.1: *Zurich Airport noise contour levels in 2005. The figure shows the 50dB noise contour for the three different metrics used in the model. Although the contours are largely overlapping, for observations in excess of the 50dB L_{eq}16h-threshold, the three metrics are only weakly correlated. The correlation coefficients are $\rho = 0.05$ between L_{eq} 16h and the L_{eq} peak metric, and $\rho = 0.038$ between L_{eq} 16h and the evening noise metric. The latter metric is weakly negatively correlated with the peak measures ($\rho = -0.14$), primarily reflecting runways alternations during the day.*

[3]The correlation coefficient between mean and peak noise exposure levels is $\rho = 0.05$. Mean exposure and evening exposure are not correlated ($\rho = 0.04$), while the evening and the peak metrics are slightly negatively correlated ($\rho = -0.14$), reflecting runways alternation.

the whole of Europe. The night-time flying ban essentially provides that there are to be no flights between the hours of midnight and 6am. As for early morning noise, significant exposure in the South-East started in late 2003. At the time of writing, not enough property transactions were available in this region to allow for the separate modelling of the morning noise effects. This is left for future work.

3.1.2 Residential Housing Sales Data

A second data set of single-family home transactions in the Canton of Zurich was provided by a regional mortgage originator. It contains 3,947 property transactions that occurred between 1995 and 2005, 759 transactions are subject to various degrees of aircraft noise. They are within the 50dB noise contour levels depicted in Figure 3.1. The rest is not subject to airport noise as previously defined and is scattered around the Canton of Zurich. In addition to the transaction prices, the records contain detailed descriptions of key features of each house, such as lot size, volume, number of rooms, age, an assessment of the state of the building and several other structural characteristics listed in Table 3.1, along with their respective descriptive statistics.

The transaction data were matched to the aircraft noise data and with several further geographic features and attributes of the location, listed and described in Table 3.2. The geographic attributes include measures of accessibility (car travel distance to the Central Business District (CBD), environmental amenities (exposition, view, steepness of the terrain), neighborhood characteristics (building density, socioeconomic composition) and measures of additional nuisances (road traffic and train noise). Note that, as with the aircraft noise, a 50dB threshold was used for the road traffic noise variable. With the help of a digital terrain model the extent of the view on two major amenities – the lakes and the Swiss Alps – were simulated for each of the 54,000 built hectares in the Canton of Zurich and matched to the property database.

Table 3.1: *Descriptive statistics of the house characteristics.*

Variable	Mean	Median	Min	Max	Std. Dev
House price [in CHF thsd.]	772.16	727.00	155.00	2,600.00	262.94
Continuous variables)					
Lot size [m^2]	521.62	447.00	150.00	2,430.00	315.61
Size, volume of building [m^3]	723.12	691.00	350.00	1,995.00	220.67
Number of rooms	5.49	5.00	2.00	11.00	1.15
Number of bathrooms	2.27	2.00	1.00	6.00	0.73
Age of building [years]	30.76	21.00	0.00	156.00	32.67
Categorical variables					
Condition of the dwelling					
New	0.36				
Renovated	0.13				
Well maintained	0.41				
Needs renovation	0.10				
Brick building	0.95				
Detached	0.46				
Cellar	0.95				
Double glazing	0.66				
Floor heating	0.45				
Garage	0.49				
Underground garage	0.25				
Modern kitchen	0.33				
Swimming pool	0.02				
Sauna	0.04				

The table reports the descriptive statistics of the 3,737 observations included in the final sample. The original data set contained 3,947 transactions single-family homes sold at arm's length in the Canton of Zurich between 1995 and 2005. 230 observations (5.8%) were excluded because of likely data entry mistakes, of which 178 transactions with very small lot sizes under 150 m^2. We suspect that for these transactions, the house living area was erroneously entered.

3.2 Empirical results

3.2.1 Explorative Spatial Analysis of the Residential Housing Sales Data

In spatial econometrics, the choice of the weighting scheme is crucial as it captures the pattern of interaction of neighbouring units. Ideally, this choice ought to be

Table 3.2: *Descriptive statistics of the location characteristics*

Variable	Mean	Median	Min	Max	Std. Dev
Aircraft noise (in excess of 50dB)					
L_{eq} 16h [dB]	1.11	0.00	0.00	20.40	2.84
L_{eq} Evening [dB]	0.24	0.00	0.00	16.10	1.25
L_{eq} 1h Peak [dB]	0.67	0.00	0.00	8.20	1.50
Location variables					
Road traffic noise, Lr 16h [dB]	0.78	0.00	0.00	18.50	2.55
View on lakes [ha]	512.00	0.00	0.00	6,971.00	1,236.00
View on Alps [km^2]	187.83	168.83	0.00	986.48	132.56
Travel distance to CBD [min]	32.9	33.00	12.00	56.00	8.01
Near power line (<200m)	0.03	0.00	0.00	1.00	0.16
Near railway (<100m)	0.09	0.00	0.00	1.00	0.28
Slope terrain [%]	4.59	3.83	0.13	21.33	3.49
Aspect: East	0.28	0.00	0.00	1.00	0.45
Aspect: West	0.44	0.00	0.00	1.00	0.50
Share of Swiss residents	0.84	1.00	0.00	1.00	0.36
Maximum built density [%]	43.48	40.00	15.00	333.00	18.89
Community tax revenue [Index]	106.78	90.93	42.34	511.42	51.95

The location variables were matched at the hectare level with each of the 3,737 single-family homes, sold in the Canton of Zurich between 1995 and 2005. The aircraft noise exposure and, where possible, the other location variables are those of the transaction year. All noise variables are reported as the values in excess of 50dB. Daytime car travel noise is measured with the Lr metric (rating level). The distance to CBD is measured as the car travel time to Zurich Main station. Aspect (orientation) dummies are computed only for terrains with a slope greater than 1%. The share of Swiss residents is computed in a neighborhood of 300m around the transaction. View variables are computed at 4 meters above ground. The density variables report the maximum allowed built density on the lot expressed as the ratio of the living space to the lot size. The community tax is the communal per capita tax revenue.

guided by theory, but in many applied settings, existing theory is compatible with several possible weighting schemes. The setting considered here suggests a weighting scheme based on the Euclidean distance between houses (with possibly a cap at a given distance), or on a contiguity metric. Euclidean distance is derived from x-y coordinates. A contiguity metric defines two observations as neighbors irrespective of their distance.

As a consequence of land-use regulation, vacant adjacent land lots tend to be developed roughly at the same time. Houses built on these lots are likely to be similar, reflecting the supply and demand conditions prevalent at the time of development (e.g. similar construction technology, demographic patterns or architectural tastes). So, unobserved house characteristics may be spatially correlated. On the other hand, both noise measurements and house locations are available to us only up to a precision of ±100 meters, which limits the use of the Euclidean distance metric and favors an approach based on contiguity. Which metric should we choose? Two exploratory techniques can guide our decision. The first – the estimation of the empirical variogram – is of help when choosing an adequate weighting scheme. The second involves the formal testing for spatial correlation.

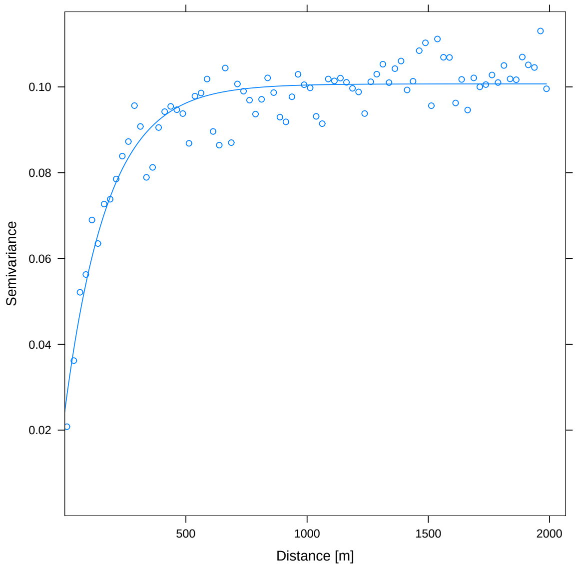
Variogram Estimates

The empirical variogram estimates the degree of spatial dependence between two locations. It is routinely used in geostatistics as a summary measure of spatial dependence, much like the correlogram is used in time series analysis to assess the degree of temporal correlation. We compute estimates for both the raw log housing prices and for the residuals of the hedonic regression of log prices on the housing characteristics and on the attributes of the location. We use a robust estimator of $\gamma(h)$ – the semivariogram at distance h – suggested by Cressie (1993). This is defined as follows. Denote with $N(h)$ all pairs of observations i, j belonging to the distance class $h = d(i,j)$, where d is a suitable distance metric. The robust semivariogram estimator $\bar{\gamma}(h)$ is given by

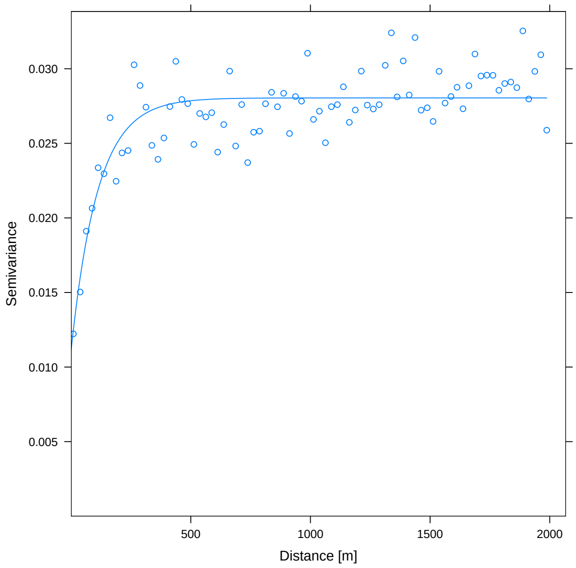
$$\bar{\gamma}(h) = \frac{1}{2\left(0.457 + \frac{0.494}{N(h)}\right)} \left\{ \frac{1}{N(h)} \sum_{i,j \;\in\; N(h)} |\hat{\varepsilon}_i - \hat{\varepsilon}_j|^{-2} \right\}. \tag{3.1}$$

The results of the empirical variogram estimation are presented in Figure 3.2.1.

The sample semivariogram $\gamma(h)$ at different distances shows a positive correlation at short lags of both the raw data (the log selling prices) and the OLS residuals. Correlation of the OLS residuals decreases rapidly with increasing distance, and the sill is reached at a distance of about 300 meters, lending some weight to the choice of a scheme based on contiguity or on a Euclidean metric



(a)



(b)

Figure 3.2: *Sample variograms for the raw log prices (a) and OLS residuals (b).*

with a cap at this distance. In the following we perform spatial analysis using three different spatial matrices; two of them based on the Euclidean distance, the third on nearest-neighbor contiguity. For the distance-based spatial weight matrix

W, define $w_{ij} = 1$ for $d_{ij} \leq c$, and $w_{ij} = 0$ otherwise, d_{ij} being the estimated Euclidean distance between i and j, and c is the cut-off value. Upon consideration of the semivariogram, the cut-off values for the distance based matrices were set at $c_1 = 300m$ and $c_2 = 600m$, respectively. Both matrices are subsequently row-standardized so that row's elements sum to one. In the third matrix the neighbor structure is constrained to the four nearest-neighbors. More than 70% of the observations have at least four neighbors within a radius of 300 meters.

Testing for Spatial Dependency and Spatial Autocorrelation

Formal testing for spatial correlation is performed with two different tests and three different spatial weight matrices. We report two variants of Moran's I classical test for spatial correlation, first proposed by CLIFF and ORD (1972).[4] The first relies on asymptotic normality while the other does not.[5] Moran's I statistic for the residuals of a linear regression $\hat{\varepsilon}$ is defined as

$$I = \frac{N \sum_{i=1}^{N} \sum_{j \neq i}^{N} w_{ij} \hat{\varepsilon}_i \hat{\varepsilon}_j}{\sum_{i=1}^{N} \sum_{j \neq i}^{N} w_{ij} \sum_{i=1}^{N} \hat{\varepsilon_j}^2}. \tag{3.2}$$

The expected value of I is $E[I] = -1/N$ and its variance is

$$Var[I] = \frac{N\left[(N^2 - 3N + 3)\, S_1 - N S_2 + 3 S_0^2\right] - b_2 J}{(N-1)(N-2)(N-3) S_0^2} - E^2\,(I) \tag{3.3}$$

where $J = [(N^2 - N) S_1 - 2 N S_2 + 6 S_0^2]$, $S_0 = \sum_{i=1}^{N} \sum_{j}^{N} (w_{ij} + w_{ji}/2)$, $S_1 = \sum_{i=1}^{N} \sum_{j=1}^{N} (w_{ij} + w_{ji})^2/2$, $S_2 = \sum_{i=1}^{N} (w_{i.} + w_{.i})^2$ with $w_{i.} = \sum_{j=1}^{N} w_{ij}$ and $b_2 = N \sum_{i=1}^{N} \hat{\varepsilon}_i^4 / (\sum_{i=1}^{N} \hat{\varepsilon}_i^2)^2$. Under general regularity conditions on the weighting matrix W, the standardized I statistic $I^* = (I - E[I])/\sqrt{Var[I]}$ is asymptotically distributed as a standard normal. The alternative inference results are based on 500 random permutations of the residual map. Computation of Moran's I statistic for the permutations provides the rank of the observed statistic and gives a consistent estimate of the p-value. In Table 3.3 we report the spatial correlation tests of the log house prices and the corresponding results for the OLS residuals. Both the

[4] Moran's I test is formally similar to the Durbin-Watson statistic and has similar optimal properties.

[5] The tests and the estimation methods used here are implemented in the R package `spdep`.

Table 3.3: *Spatial correlation tests*

Spatial weight matrix	Moran's I	p-value	MC simulation	p-value
Log house prices				
Euclidean, cut-off 600m	0.3250	<0.001	0.3512	<0.001
Euclidean, cut-off 300m	0.3025	<0.001	0.3064	<0.001
Nearest-neighbor (NN=4)	0.3422	<0.001	0.3528	<0.001
OLS residuals				
Euclidean, cut-off 600m	0.1441	<0.001	0.1557	<0.001
Euclidean, cut-off 300m	0.1368	<0.001	0.1363	<0.001
Nearest-neighbor (NN=4)	0.1457	<0.001	0.1534	<0.001

The spatial correlation tests are computed for both the raw data and the residuals of the OLS estimation of the basic hedonic model. The statistics are reported for three different specifications of the spatial weight matrix. The first two spatial matrices are based on an Euclidean norm, with cut-off points at 300 and 600 meters, respectively. The third is a contiguity matrix where we consider the four nearest neighbors.

normal approximation and the bootstrap tests very clearly reject the null of the absence of spatial correlation in the house price data and in the OLS residuals. The I statistics are similar across all three different spatial weighting matrices under consideration. We conclude that – from the point of view of statistical inference – the explorative analysis and the correlation tests strongly points to the need of incorporating the spatial structure of the data into the empirical analysis.

Spatial Specification Tests

This subsection is devoted to the choice of the spatial model specification. We here follow the approach sketched in Subsection 2.2.2 when choosing between the two spatial models considered in the literature: the spatial lag model and the linear model with spatial autocorrelation. The results are reported in Table 3.4. The first entry in the table (LM_ρ^*) summaries the results of the test for endogenous spatial lag dependence (see equation (2.6). The alternative statistic, denoted LM_ρ^*, tests for the presence of a spatial AR error process. For the three spatial matrices under consideration, both tests reject their respective null hypothesis, with one exception. The absence of spatial dependency cannot be rejected at the shortest range (300m).

Table 3.4: *Spatial specification tests*

Spatial weight matrix	LM^*_ρ	p-Value	LM^*_λ	p-Value
Euclidean, cut-off 600m	1.88	0.180	136.11	<0.001
Euclidean, cut-off 300m	15.46	<0.001	249.34	<0.001
Nearest-neighbor (NN=4)	8.45	0.004	210.48	<0.002

The spatial specification tests are performed with three different specifications of the spatial weight matrix. Lagrange Multiplier statistics are reported with their marginal significance levels.

Notice that the rejection is much stronger for the autocorrelation test, as apparent from the higher Lagrange Multiplier statistic. In this case, Florax, Folmer and Rey (2003) argue for the specification of a model without lagged endogenous variable and with a spatial autoregressive error structure. We follow here their advice.

3.2.2 Estimation of the Spatial Model

On the strength of the analysis in the previous section a spatial model is fit to the GIS-augmented single-family home data set. The error follows a SAR process as in equation (2.2). We report the results of Maximum Likelihood estimation of the spatial model in Table 3.5 (Model 1 and 2) for different specifications of the aircraft noise, alongside the results of the OLS estimation of a non-spatial specification (Model 3).[6]

All estimated regressions show a satisfactory overall goodness-of-fit, as illustrated by the low standard errors of estimation (12.8% for Model 1). Structural and location attributes of the houses are strongly significant and have the expected sign, the principal characteristics driving house prices being the volume (size) of the building, its age, lot size and the centrality of location.[7] The elasticity of sale prices with respect to the travel time to the Zurich CBD is −0.231, meaning that

[6]ML estimation requires the repeated evaluation of the information matrix, which is computationally demanding in this context (Pace and Gilley, 1998). Therefore, we use a sparse matrix implementation.

[7]For reasons of space, both the time and the community dummies are not reported. They are available from the author upon request.

a one minute increase from 10 to 11 minutes will cut the sale price of a CHF 1 million home by approximatively CHF 20,600. Properties with a extended view over a lake command a high premium, up to 15%, other things being equal. This premium is much higher than the one paid for an extended view on the mountains, possibly reflecting the relative abundance of such views in Switzerland.[8]

Noise discounts

Aircraft noise exposures may enter the hedonic regression with several specifications. In the first specification (Model 1), only the mean daytime noise exposure enters the hedonic regression. This is the basic specification considered in the meta-analysis of Schipper, Nijkamp and Rietveld (1998) and in Nelson (2003). In this case, the corresponding Noise Depreciation Index (NDI) is 0.97%, i.e. a noise increase of 1 dB corresponds to a 0.97% lower house prices. Noise is highly significant. The standard deviation of the NDI is low at 0.12%. The 95% confidence interval (0.68%-1.17%) encompasses the average NDI of 0.83% reported by Schipper, Nijkamp and Rietveld (1998).[9] However, our NDI estimate is substantially higher than the average cumulative noise discount of 0.5% to 0.6% reported by Nelson (2003). It is close to the NDI of 0.7% found by Baranzini and Ramirez (2005) in a recent study based on rental apartments located in the vicinity of Geneva airport.

In addition to the results of the base model, Table 3.5 also reports results for the full noise exposure specification (Model 2). Again, the hedonic regression measures this impact quite precisely, as signalled by the small standard errors, which are adjusted for spatial autocorrelation. All the noise exposure measures, i.e the mean and peak noise exposure (as captured by the L_{eq}16h and L_{eq}max) and evening noise are statistically highly significant. An increase in mean daytime noise exposure of 1 dB is associated with a decrease in prices of 0.70%. An independent 1 dB

[8] Notice that view is defined as the maximum number of hectares visible from a given location (obstacles as trees or other buildings are not accounted for in this simulation). This is a very crude metric to judge the attractiveness of a view. In particular, it is independent of the distance of the point of interest.

[9] Schipper, Nijkamp and Rietveld (1998) also report a regression of the NDI on housing wealth, measured as the mean house price divided by per capita income. For our sample we would expect a higher than average NDI of -1.2%, reflecting the comparatively high housing wealth in the region of Zurich.

increase in evening noise exposure impacts prices with -0.64%. A similar increase in peak noise knocks off 0.63% from the price.

Although aircraft noise has an evident impact on house prices, the overall noise discounts are of relatively moderate magnitude. Based on either the base of the fully specified model estimates, typical discounts are in the -2% to -8% range. Only 10% of the discounts are in excess of -10%.

Relatively few dwellings are subject to very high noise levels. Single-family homes tend to be built on prime (i.e. less noisy) locations. Areas heavily affected by aircraft noise typically attract other types of developments, like, e.g., offices and logistic property. Finally, we notice that in the base specification, the NDI for road traffic is -0.53% (standard error 0.11%). Adding an extra dB of motor vehicle noise affects property prices slightly less than aircraft noise.

Spatial estimation

Although the spatial tests clearly reject the absence of spatial correlation, the difference between the OLS and the spatial regression results is minimal. This is visible in Table 3.5 where we compare the previous results of Model 1 and Model 2 with those of an OLS regression (Model 3). Inference based on the OLS residuals is virtually unchanged, despite the fact that the standard errors are not corrected for spatial correlation. The reason for the modest contribution of spatiality is evident when we consider the magnitude of the spatial autoregressive parameter ρ, reported at the bottom of the table. The point estimate is $\rho = 0.185$ indicating only a weak positive correlation between errors of adjacent locations. Indeed, from equation (2.3) recall that the variance-covariance matrix for the random vector ε is proportional to the product of the inverse matrix $(I - \rho W)^{-1}$ with its transpose. This matrix can be expanded as follows

$$(I - \rho W)^{-1} = I + \rho W + \rho^2 W^2 + ... \tag{3.4}$$

With weights $\rho = 0.185, \rho^2 = 0.034$, the higher terms in the expansion quickly decay. In other words, the spatial autocorrelation component – although statistically highly significant – is small from an economical point of view. Accordingly, its impact on inference results is negligible.

In spatial econometric applications the choice of spatial matrix may cause greater differences in parameter estimates than the choice of estimation technique. This is unsatisfactory as this choice remains largely untested and many possible matrices are compatible with the underlying economic story. We thus conclude the spatial econometric section by reporting the results of the estimation of Model 1 given alternative choices for the spatial matrices. The results are reported in Table 3.6, in the columns labelled Model 4 (for the weighting matrix with cut-off at 600m) and Model 5 (for the weighting matrix based on nearest-neighbor contiguity).

Both alternative weighting matrices are associated with marginally higher, positive spatial autocorrelation parameters ρ. Accordingly, the standard error of the estimated coefficients are somewhat higher. Nevertheless, as far as the added value of the spatial econometric specification is concerned, this analysis confirms the previous negative results.

Robustness of Results

Higher noise levels may exert a disproportionate impact on house prices – an effect not captured by a crude linear specification. In order to examine this issue we reformulate Model 1 as a generalized additive model. This nonparametric estimation method relaxes the assumption of log-linearity of the mean noise exposure, allowing for a more flexible functional form (Hastie and Tibshirani, 1990). The nonparametric component is modelled as a third-order spline. Figure 3.3 illustrates the result of the estimation where we report the non-parametric fit with the respective 95%-confidence interval.

The visual inspection of the results shows that non-parametric specification is broadly supportive of the log-linear assumption. Nonetheless, the slightly S-shaped fitted spline points to a more than proportional effect at both the lower and the higher end of the noise distribution, i.e. for L_{eq} levels between 52 and 55 dB and for exposures higher than 65 dB, respectively. Interestingly, this confirms (at least informally) results in the acoustic literature which have also identified non-linearities at equivalent thresholds.[10]

[10] For example, a similar response pattern is found in a study based on a questionnaire survey sent to residents in the vicinity of Zurich airport (Wirth, Brink and Schierz, 2006).

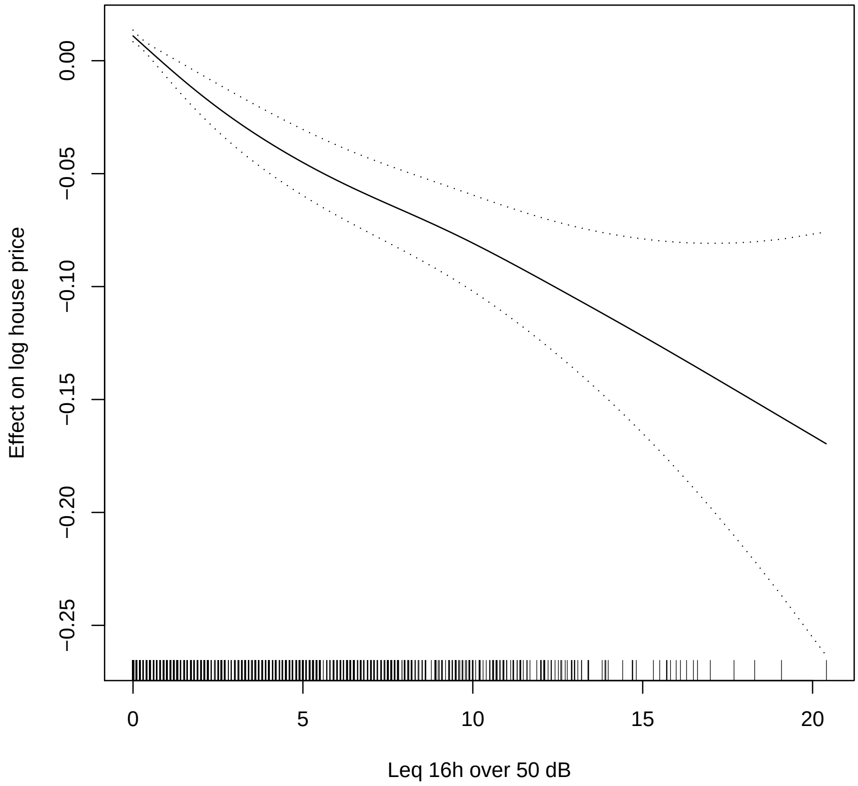


Figure 3.3: *Non-parametric estimation of the impact of mean noise exposure. The nonparametric component is modelled as a third-order spline. The dotted lines represent the 95% confidence interval.*

As a further challenge to the stability of the result, we re-estimate Model 1 with an interaction effect between time and the mean noise exposure. The estimated interaction term is plotted in Figure 3.3. A visual inspection of the results shows some increase in the NDI since the year 2000, which - incidentally - is the year when the bilateral agreement between Switzerland and Germany was terminated. However, our preferred NDI estimate (0.97%) is within the 95% confidence interval of all time-specific NDI estimates. This shows that the NDI is reasonably stable over the years.

Finally, we turn the focus of the analysis to the contribution of the geographical

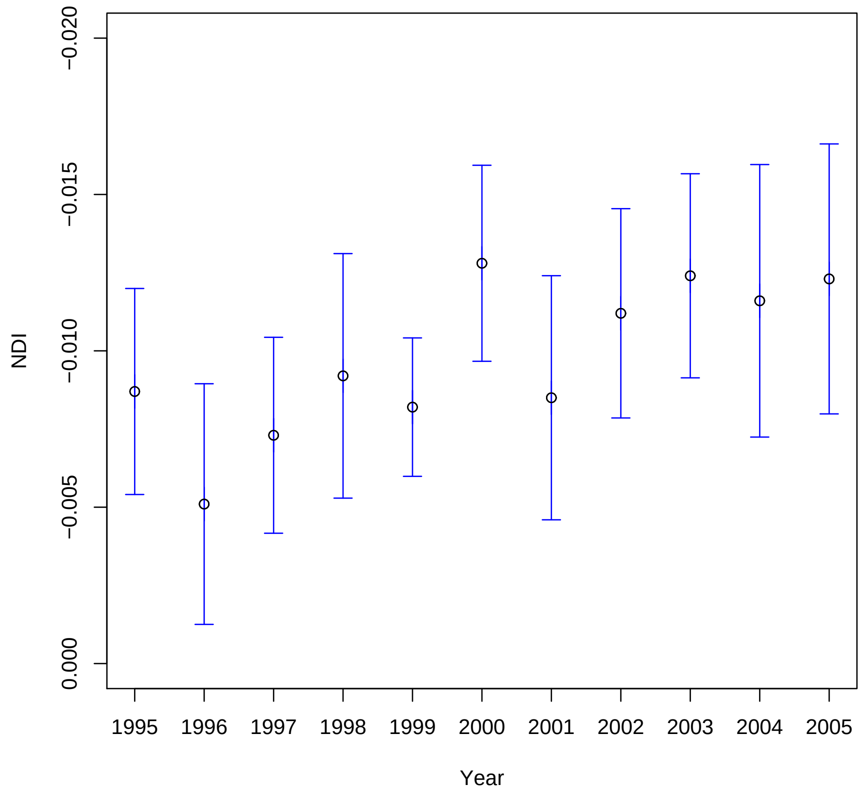


Figure 3.4: *Estimated interaction effect between time of transaction and NDI. The error bars represent the 95% confidence interval. The base-case NDI (0.97%) is within the 95% confidence interval of all time-specific NDI estimates.*

variables to the precision of our estimates. Notwithstanding the growing availability of GIS-coverage, the gathering of a wide range of spatially referenced data remains costly. It thus makes sense to compare the explanatory power of the regression with the GIS-matched location variables to the much cheaper modelling alternative which only includes an indicator variable for each one of the 171 communities in the Canton of Zurich. In the latter case, indicator variables act as a catch-all for the location characteristics, which are assumed not to vary within a community. Still, aircraft noise variables are matched to a precise location. The results of this specification are presented in the last two columns of Table 3.6.

Casual inspection of the results indicates that the implicit prices of the structural attributes (size, age, quality etc.) are very close to those obtained with the fuller specifications. The suppression of the location variables exerts a weak impact on the remaining geo-referenced variable, aircraft noise. Although the noise coefficient remains strongly statistically significant, the NDI drops somewhat to 0.86%. However, the general fit of the model does not worsen, as signalled by the higher log likelihood and the slightly higher standard error of regression. As the aircraft noise exposure is limited to specific communities adjacent to the airport, the inclusion of community fixed-effects captures a significant part of the noise variation. Richer specifications which include geo-referenced variables allow us to avoid this masking effect.

3.3 Conclusions of Part I

The purpose of this work is to evaluate the impact of aircraft noise on the housing prices in the Zurich Airport area applying spatial econometric techniques. Based on a large and detailed sample of single-family homes transactions we find a NDI of slightly under 1% per extra dB. This is a comparatively high estimate, at least when confronted with the results surveyed by Nelson (2003) which covers 33 studies for 23 airports in North America. A possible explanation for the high Swiss NDI value - other than pure sample variability - is the income effect evidenced in Schipper, Nijkamp and Rietveld (1998). The studies surveyed in Nelson (2003) stem for the great majority from the 1970s, the most recent study uses data from the early 1990s. During the last two decades, rising incomes may have increased demand, if, as it is likely, quietness is a superior good. An alternative interpretation is related to the noise measurement issue. Thanks to advances in aerodynamics and engineering, newer airplanes are now significantly quieter. This noise reduction has had a strong impact on aircraft noise as measured by the L_{eq} metric. Indeed, the number of noise events enters the L_{eq} metric only logarithmically, while the intensity of the event has a linear impact on it. Home-owners may average the noise events in a different way than implicitly assumed by this metric. If the noise effectively perceived by home-owners has stayed more or less constant over the years, our somewhat higher estimates could be partly offsetting the lower measured L_{eq}. Inspection of Figure 3.4. also suggests a slightly higher NDI towards the end of the sample which coincides with generally lower mean exposure levels.[11] We leave this question as a topic for further research.

As spatial correlation in the OLS residuals was detected, several estimation techniques suggested by the relatively new and emergent spatial econometric literature have been applied. The noise estimates are robust to different choices of spatial weighting matrix and to different methods of estimation. From an economic point of view, the added value of the spatial econometric technique is negligible. However, real estate research has to cope with the potential misspecification induced by the spatial nature of the data. From this point of view, spatial statistics does at least increase the level of confidence in the results. There are, however, alternative ways to measure the impact of noise which may be even less prone to misspecification biases. The sudden and unexpected change of runways at Zurich Airport has exposed some neighbourhoods to aircraft noise which had been so far free from it. This natural experiment setting suggests the use of a difference-in-differences (DID) estimator. As already pointed out earlier, at the time of writing, not enough property transactions were available in this region to allow for a specific modelling. This, as well, is left for future work.

Of course, this analysis is not yet sufficient for a balanced evaluation of the welfare costs associated with aircraft noise, as it merely estimates the hedonic price of noise and does not attempt to identify the demand for quietness. Almost thirty years after the publication of Rosen's seminal paper, the issues regarding the full identification and estimation of hedonic models have only been recently clarified by the works of several researchers (Ekeland, Heckman and Nesheim, 2002; Bajari and Kahn, 2002, among others). We address this issue in the following essay.

[11] In the first half of the sample (1995-2000) a quarter of the transactions in the airport perimeter were subject to a daytime L_{eq} in excess of 8.2 dB. In the second half of the sample the 25%-percentile was equal to 7.2 dB.

Table 3.5: *Estimation results: SAR models and non-spatial hedonic regression*

	Model 1 (ML SAR)		Model 2 (ML SAR)		Model 3 (OLS)	
Variable	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	9.2801	0.1337	9.3899	0.1083	9.2325	0.1253
L_{eq} 16h	-0.0098	0.0010	-0.0070	0.0013	-0.0098	0.0009
L_{eq}Evening			-0.0064	0.0019		
L_{eq} 1h Peak			-0.0063	0.0023		
Age of building	-0.0028	0.000	-0.0029	0.0003	-0.0026	0.0003
Age squared	0.0007	0.000	0.0007	0.0002	0.0006	0.0002
New	0.1377	0.012	0.1373	0.0116	0.1358	0.0119
Renovated	0.1451	0.009	0.1452	0.0093	0.1419	0.0096
Well maintained	0.1126	0.008	0.1125	0.0080	0.1096	0.0082
Brick building	0.0284	0.009	0.0290	0.0092	0.0298	0.0094
Detached	0.0256	0.006	0.0264	0.0056	0.0253	0.0057
Cellar	0.0476	0.010	0.0478	0.0103	0.0487	0.0106
Double glazing	0.0312	0.005	0.0317	0.0055	0.0322	0.0056
Floor heating	0.0356	0.006	0.0359	0.0064	0.0357	0.0066
Garage	0.0253	0.005	0.0257	0.0055	0.0253	0.0056
Underground garage	0.0290	0.007	0.0293	0.0071	0.0264	0.0072
Modern kitchen	0.0589	0.005	0.0586	0.0052	0.0592	0.0054
Swimming pool	0.0637	0.015	0.0641	0.0147	0.0653	0.0152
Sauna	0.0396	0.011	0.0396	0.0109	0.0379	0.0113
Log lot size	0.1691	0.006	0.1692	0.0059	0.1646	0.0060
Log size	0.4163	0.011	0.4155	0.0111	0.4206	0.0113
Log rooms	0.1243	0.013	0.1246	0.0130	0.1223	0.0134
Log bathrooms	0.1005	0.008	0.0998	0.0078	0.1018	0.0080
Share Swiss residents	0.0149	0.006	0.0157	0.0064	0.0159	0.0063
Road traffic noise	-0.0050	0.001	-0.0051	0.0009	-0.0053	0.0009
Log travel dist. to CBD	-0.2310	0.015	-0.2354	0.0151	-0.2290	0.0133
Low density (<40%)	-0.0034	0.006	-0.0040	0.0059	-0.0044	0.0056
Middle density (40-50%)	-0.0024	0.007	-0.0029	0.0068	-0.0034	0.0065
Higher density (>50%)	-0.0117	0.007	-0.0126	0.0072	-0.0132	0.0070
Lake view >0-20 km^2	0.0552	0.007	0.0514	0.0066	0.0563	0.0059
Lake view 20-40 km^2	0.1390	0.012	0.1346	0.0118	0.1411	0.0107
Lake view >40 km^2	0.1121	0.014	0.1074	0.0138	0.1103	0.0120
View 50-100 km^2	0.0359	0.009	0.0357	0.0091	0.0406	0.0084
View 100-250 km^2	0.0236	0.008	0.0244	0.0078	0.0270	0.0071
View >250 km^2	0.0163	0.009	0.0183	0.0090	0.0159	0.0081
Slope 0-9%	0.0194	0.006	0.0191	0.0061	0.0191	0.0060
Slope > 9%	0.0357	0.008	0.0360	0.0080	0.0353	0.0076
Near power line	-0.0103	0.015	-0.0133	0.0150	-0.0118	0.0140
Near railway	-0.0243	0.008	-0.0237	0.0082	-0.0247	0.0078
Aspect: East	-0.0032	0.007	-0.0034	0.0068	-0.0002	0.0064
Aspect: West	0.0102	0.006	0.0093	0.0063	0.0139	0.0060
Log tax revenue	0.1559	0.010	0.1568	0.0099	0.1549	0.0089
ρ	0.1852		0.1853		-	
LR test (p-value)	<0.001		<0.001		-	
Residual standard error	0.1279		0.1275		0.1309	
N	3737		3737		3737	
Log likelihood	2364		2374			
AIC	-4625		-4640			

For reasons of space, yearly time dummies are not reported here. They are available from the author upon request.

Table 3.6: *ML SAR estimation results with alternative weighting schemes.*

	Model 4 (c=600m)		Model 5 (NN)		Model 6 (No GIS)	
Variable	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	9.3800	0.1137	9.3701	0.1124	9.3226	0.0840
L_{eq} 16h	-0.0099	0.0011	-0.0099	0.0010	-0.0086	0.0023
Age of building	-0.0030	0.0003	-0.0030	0.0003	-0.0034	0.0003
Age squared	0.0008	0.0002	0.0008	0.0002	0.0010	0.0002
New	0.1359	0.0116	0.1367	0.0116	0.1271	0.0117
Renovated	0.1443	0.0093	0.1448	0.0092	0.1491	0.0093
Well maintained	0.1119	0.0080	0.1119	0.0080	0.1111	0.0080
Brick building	0.0290	0.0093	0.0278	0.0093	0.0280	0.0093
Detached	0.0277	0.0056	0.0271	0.0056	0.0267	0.0057
Cellar	0.0468	0.0103	0.0458	0.0103	0.0441	0.0104
Double glazing	0.0340	0.0055	0.0326	0.0055	0.0291	0.0055
Floor heating	0.0333	0.0064	0.0349	0.0064	0.0326	0.0065
Garage	0.0254	0.0055	0.0259	0.0055	0.0278	0.0056
Underground garage	0.0270	0.0071	0.0289	0.0072	0.0287	0.0073
Modern kitchen	0.0587	0.0053	0.0585	0.0052	0.0634	0.0053
Swimming pool	0.0598	0.0147	0.0624	0.0147	0.0587	0.0149
Sauna	0.0391	0.0109	0.0378	0.0109	0.0526	0.0110
Log lot size	0.1700	0.0059	0.1693	0.0060	0.1786	0.0059
Log size	0.4165	0.0111	0.4158	0.0112	0.4223	0.0113
Log rooms	0.1199	0.0130	0.1207	0.0130	0.1246	0.0131
Log bathrooms	0.0960	0.0077	0.0969	0.0077	0.0969	0.0078
Share Swiss residents	0.0160	0.0064	0.0169	0.0066		
Road traffic noise	-0.0053	0.0009	-0.0054	0.0009		
Log travel dist. to CBD	-0.2335	0.0162	-0.2307	0.0159		
Low density (<40%)	-0.0077	0.0059	-0.0045	0.0060		
Middle density (40-50%)	-0.0065	0.0068	-0.0027	0.0069		
Higher density (>50%)	-0.0145	0.0072	-0.0120	0.0073		
Lake view >0-20 km^2	0.0545	0.0067	0.0557	0.0067		
Lake view 20-40 km^2	0.1318	0.0123	0.1357	0.0122		
Lake view >40 km^2	0.1080	0.0146	0.1119	0.0144		
View 50-100 km^2	0.0319	0.0092	0.0344	0.0093		
View 100-250 km^2	0.0213	0.0081	0.0216	0.0080		
View >250 km^2	0.0135	0.0093	0.0137	0.0092		
Slope 0-9%	0.0171	0.0060	0.0177	0.0061		
Slope >9%	0.0357	0.0080	0.0345	0.0081		
Near power line	-0.0090	0.0151	-0.0064	0.0154		
Near railway	-0.0244	0.0080	-0.0228	0.0083		
Aspect: East	-0.0032	0.0068	-0.0031	0.0069		
Aspect: West	0.0093	0.0063	0.0106	0.0065		
Log tax revenue	0.1588	0.0107	0.1599	0.0105		
ρ	0.2579		0.2233		0.1453	
LR test (p-value)	<0.001		<0.001		<0.001	
Residual standard error	0.1276		0.1274		0.1263	
N	3737		3737		3737	
AIC	-4640		-4645		-4439	

Model 4 uses a contiguity matrix with a cut-off value set at 600m, while in Model 5 it is constrained to the four nearest neighbors. For Model 6 the same weighting matrix as in Model 1 of Table 5 is used, with GIS-matched location variables replaced by community indicator variables. For reasons of space, both the time and the community dummies are not reported.

Part II

The Demand for Housing Attributes and Environmental Amenities

Chapter 4

Hedonic Modelling: Taking the Next Step

4.1 Introduction

Reliable assessments of the demand for the characteristics of housing units are important inputs to city planners, real estate developers and environmental agencies. They may be of some interest to the general public, too. Issues such as the reduction of traffic noise and pollution, the preservation of open spaces and the segregation of households along income or social lines often hit the front pages. These issues may benefit from a correct measurement of the demand for location characteristics and environmental amenities.

This essay proposes a structural hedonic model to estimate the marginal willingness to pay for the main housing characteristics and the attributes of the location in a cross-section of households located in the Greater Zurich area. The main goal is the measurement of the preference parameters of home owners. As an illustration of the results, we verify some key assumptions of the amenity-based location theory presented by Brueckner, Thisse and Zenou (1999). This theory predicts that the relative location in a city of different income groups crucially depends on the spatial pattern of the amenities.

4.1.1 Structural Hedonic Model

Hedonic models relate the price of a good and its demand to the characteristics of the good rather than on the good itself. Hedonic models are now routinely used to evaluate differentiated products, like houses, cars or computers. In a hedonic house price model (as presented in Part I of this thesis), the house price is related to the characteristics of the property, such as size, quality, and the attributes of its location. A *structural* hedonic model is more informative than a conventional hedonic model because it tells us how the hedonic price function would change if an underlying parameter changes. So, if we know the distribution of tastes for some house characteristics, we might use it to predict the response in prices following, say, a change in tastes following a change in the demographic composition of the population. We call *identification* the process of recovery of unknown structural parameters from a statistical model, e.g. from the hedonic price model. The purpose of identification is the estimation of the structural model because its parameters may have implications for economic policy.

At least three fundamental features of real estate assets hamper the identification of a structural hedonic model: heterogeneity, indivisibility and lack of liquidity. Heterogeneity refers in this context to the preferences of the consumers and to the suppliers' production technology. Allowing for heterogeneity in preferences means that the analysis is not carried in terms of a single, representative consumer but that differences in preferences (i.e. tastes) are considered explicitly.[1] This relates to the estimation of a structural hedonic model in the following way. By their nature, real estate assets are indivisible bundled goods. Clearly, buying two two-bedroom apartments is not the same as buying a four-bedroom one. The (marginal) price of a bedroom may depend on the total size of the apartment. This contrasts with standard consumer theory in which equilibrium results in a linear price system.[2] Hence, if consumers have different tastes, they will face different prices at the margin for the same characteristic. Therefore, the desired natural experiment in which a consumer of a given taste faces exogenous price

[1]Note that the differences can be observed (to the econometrician) or unobserved. With observed heterogeneity differences in behavior reflect actual observable differences in tastes rather than measurement errors.

[2]If the bundling property does not apply, consumers can generally force linearity of the pricing function through arbitrage. This is assumed impossible in the analysis of hedonic markets.

shifts cannot be readily implemented, the price being a choice variable.[3] In other words, consumers will move to houses or locations endowed with characteristics that match their preferences. If we use the observed price differentials to infer the value that consumers put to an amenity or a characteristic, we must be aware that the consumer's heterogeneity and sorting drives a wedge between the valuation of the population at large (i.e. average marginal willingness to pay) and the marginal valuation set by those consumers most willing to enjoy the amenity.

The lack of liquidity of real estate assets adds to the difficulty of estimating demand functions. Real estate assets are illiquid because of their durability and high transaction costs. Thus, typically, only a small number of choices is observed per household - often just one - barring the use of panel estimation methods. Again, we have to find alternative sources of variation from which demand and supply parameters can be estimated. Alternatively, identifying restrictions have to be placed on the choice structure of consumers.

Finally, as a consequence of the heterogeneity of the housing stock, the estimation of the demand for housing characteristics is likely to suffer from omitted variable bias. The econometrician might not observe all the relevant attributes of the location. In the case of an unobservable amenity, consumers are getting more for the price they pay than the econometrician takes into account. The estimated price elasticity is biased towards zero.

4.1.2 Existing Literature and Plan of this Part

The literature on the estimation of hedonic models is well-established (see e.g. the surveys by Boyle and Kiel (2001), Palmquist (2006) and the recent monograph of Baranzini, Ramirez, Schaerer and Thalmann (2008). However, the great majority of the empirical work has focused on the estimation of the hedonic price regression. This is only the first of the two-step identification method suggested by Rosen (1974) in his path-breaking paper. Comparatively fewer empirical papers have tried to recover preference and production technology parameters, i.e. to

[3] This problem also arises if the consumers' marginal utility of consuming the amenity or the house characteristic varies with income, as it is likely.

estimate a structural hedonic model.[4] Recently, economists have started to address the issues of preference heterogeneity and unobservable attributes (witness the contributions to the theory by Berry, Levinsohn and Pakes, 1995; Heckman, Matzkin and Nesheim, 2003a; Bajari and Benkard, 2005, among others).

Still, there are just few empirical uses of this method in the context of housing (Bajari and Kahn, 2004; Ferreira, 2004; Bayer, Ferreira and McMillan, 2007). This essay applies this new methodology to the estimation of the demand for housing characteristics of households located in the Greater Zurich Area. The framework is derived from the preference inversion approach pioneered by Bajari and Benkard (2005) and Bishop and Timmins (2008). It accounts for the aforementioned fundamental features of housing goods, thus allowing the marginal willingness to pay (MWTP) to freely differ across consumers. This is achieved through the nonparametric identification and estimation of the hedonic model. Location variables are matched to the data with the help of a GIS.

This and the following chapter are organized as follows: section 4.2 describes in non-technical terms the identification of hedonic models. It discusses Rosen's suggested approach in the light of the new contributions of the literature. In section 4.3, a more formal approach is taken. A hedonic model is set up and the equilibrium condition is derived for the special case where there is heterogeneity in the preferences of the agents. The equilibrium condition reveals the nature of the hedonic model as a sorting equilibrium. The section considers then the identification of a hedonic model with heterogenous consumers. Chapter 5 is devoted to the empirical implementation of this structural hedonic model. For a detailed sample of transactions of single-family homes located in the Greater Zurich area, the structural hedonic model is estimated. In particular, we recover the MTWP for two important location characteristics, centrality and proximity to a major exogenous environmental amenity, the Lake of Zurich. We define centrality as the proximity to the city center and its Central Business District. We then report how the MWTP varies as a function of the home owners' socioeconomic characteristics. We finally comment the result in the light of Brueckner, Thisse and Zenou (1999) amenity-based theory of location by income. We close the chapter with a

[4] See, among earlier studies, Awan, Odling-Smee and Whitehead (1982) and Kaufmann and Quigley (1987). For later contributions see Sheppard (1999) and the references therein.

section discussing the limitations and possible extensions of our approach.

4.2 Identification of Hedonic Models

This section gives a (possibly) intuitive, non-technical introduction to the issues treated by the recent literature on the identification of hedonic models. The literature goes back to Rosen's (1974) derivation of an equilibrium price function for differentiated goods in a competitive economy.[5]

In his path-breaking paper, Rosen derives the hedonic pricing function as the solution of the optimization problem of heterogenous consumers and producers trading a differentiated good. Rosen's main contribution is to show, under general regularity conditions, that the hedonic pricing function is the solution of a second order differential equation that matches demand and supply densities at each level of the good's characteristics. Thus, equilibrium in the housing market requires a hedonic price function that equates supply and demand for every existing type of houses. In general, as pointed out in Epple (1987), the equilibrium price function will depend both on the distribution of the observed and unobserved parameters which characterize the preferences of the consumers and the technology of the suppliers. This dependency is made clear by the following extreme example (Sheppard, 1999). Suppose that there is a variety of consumers but only one type of producers, so that there is no heterogeneity in production. In this case, in equilibrium, every producer has the same marginal cost at each level of the good's characteristics. The marginal hedonic price is then equal to marginal cost and the hedonic price function traces out the cost function. The same argument applies if there is homogeneity on the consumer's side. However, with heterogeneity on the one and/or the other side of the market, this will not be case. The hedonic function is in general a complex combination of both the producers' and the consumers' "deep" structural parameters.

Rosens's paper also considers a method to estimate the demand and supply functions for the characteristics. As such it has been relevant to empirical work, too. In the first step of his suggested estimation method, a hedonic price function

[5] A special case of a hedonic model with heterogenous agent was first analysed by Tinbergen (1956). The estimation of hedonic price functions goes back at least to Waugh (1928).

would be estimated by regressing the price of the composite good on its characteristics. In the second step the estimated hedonic prices would be taken as if they were actual prices and combined with household characteristics and observed household choices to estimate the marginal willingness to pay for the characteristics.

Over the years this two-step approach has drawn several criticisms, casting some doubts on its validity. BARTIK (1987) and EPPLE (1987) raised an important endogeneity issue due to the fact that in a hedonic model there is no exogenous variation on prices. The response of the consumer to changes in prices, i.e. the demand function, cannot be readily estimated since the price itself is a choice variable. This endogeneity is rooted in the sorting mechanism that lies at the core of the hedonic equilibrium. Consumers of different tastes will buy different bundles of the same characteristics. Because differentiated goods are bundled goods, each consumer faces different marginal prices. In this case, the demand system cannot be estimated by 2SLS in a single cross-section, because the heterogeneity is correlated with the buyers' traits.

A similar identification issue arises in the presence of unobserved attributes of the goods. Households are likely to know the values of some characteristics of the good that are unobserved by the econometrician. If these attributes are valuable to consumers, the price will be correlated with the amount of (unobserved) characteristics. Omitting attributes that are related with both price and quantity will bias the estimated willingness to pay of those attributes.

Recently, this particular endogeneity issue, and more broadly, the identification of demand systems for differentiated products has attracted intensive research, linking insights matured in the field of Industrial Organization (IO) to the housing market literature.[6] As noted by BAJARI and BENKARD (2005), it is quite common in IO to observe apparent violations of the revealed preferences axiom, where there is positive demand for a product dominated by other products in every observed dimension *and* which still commands a higher price. In this case, no deterministic demand system can be rationalized, unless omitted attributes are explicitly taken into account. The dominance issue is *a priori* equally likely to arise in a housing context. Taking as an example the sample of housing transactions described in

[6]See ACKERBERG ET AL. (2005) for a comprehensive survey of the recent identification and estimation techniques developed in the IO literature.

the empirical part of this work, about 15% of the observations are dominated in fifteen recorded dimensions while commanding higher prices than at least one of the dominating properties.

Three distinct but related strands of the literature have recently addressed the identification issue. Each approach stresses the importance of clearly stated identifying assumptions. They are part of an important on-going research program in econometrics that seeks to clarify the identifying restrictions necessary to draw inferences about behavioral parameter of interest (Keane, 2003). The first strand works within the setting of random utility models with unobservable characteristics. As a major departure of Rosen's approach, the consumer's decision is modelled as a discrete choice (McFadden (1977), Berry, Levinsohn and Pakes (1995), Bayer, Ferreira and McMillan (2007)). By exploiting general equilibrium conditions the latter authors are able to recover the full distribution of preferences for observed and unobserved attributes from the households choices. The second strand is centered around the work by Bajari and Benkard (2005) who consider an alternative with a continuum of choices. They recover the distribution of preferences nonparametrically from a single cross-section by imposing restrictions on the utility function, first of all separability. Following on an important result by Matzkin (2003) in the nonparametric econometric literature, they obtain an estimate of the unobservable demand component from the assumption that prices must be strictly increasing in this component conditional on other x's. They apply this methodology to the welfare evaluation of urban sprawl and to racial segregation in cities (Bajari and Kahn, 2002, 2004). Heckman, Matzkin and Nesheim (2003a) also drawing on Matzkin (2003) achieve identification in a single cross-section for both additive and non-additive hedonic models by exploiting the intrinsic nonlinearity of the hedonic model under heterogeneity. However, their results are limited to the special case of a single attribute observed without error. To the best of our knowledge, this work has not yet spurred an empirical application.

4.3 Derivation of the General Hedonic Model under Heterogeneity

4.3.1 Hedonic Sorting Equilibrium

In this section we sketch the standard hedonic model due to Rosen (1974), following closely the presentation in Heckman, Matzkin and Nesheim (2003a). These authors consider a hedonic model in a labor market setting which we restates in a real estate context, with home buyers matching to home builders. Both the buyers and the building companies are heterogenous, meaning that the utility of the consumers and the technology of the firms depend on observable and unobservable characteristics. The house characteristics are known with certainty, the heterogeneity being limited to the buyers' and builders' characteristics – an assumption relaxed later.

A house j is defined as a finite dimensional vector of characteristics x_j. Each buyer i has income utility u_i given as $u_i = u(c_i, x_j; \beta_i)$, where c_i is non-housing consumption and $\beta_i = (z_i, \varepsilon_i)$ is a vector of observed (systematic) and unobserved (idiosyncratic) individual characteristics. A builder k is similarly characterised by a cost function $C_k = C(x_j; \gamma_k)$, $\gamma_k = (y_k, \nu_k)$ summarizing again both observed (y) and unobserved characteristics (ν). The preference parameters of the buyers have distributions $\beta \sim F(z, \varepsilon)$. The technology parameters of the builder are distributed $\gamma \sim F(y, \nu)$.

Suppose as in Heckman, Matzkin and Nesheim (2003a) that the heterogeneity factors ε and ν are independent from the observable characteristics z and y. Each buyer solves the following constrained maximization problem

$$\max u(c_i, x_j; \beta_i), \text{ s.t. } c_i + p_j = E_i, \tag{4.1}$$

with $p_j = p(x_j)$, the hedonic price function, and E_i the buyer's income.
Assume that the utility function is twice differentiable and substitute for c in the utility function while dropping the individual index for convenience. Further assume for further ease of exposition that the quantity of the housing services can be summarised in a single index, x. We obtain the unconstrained maximization

problem where the indirect utility function depends on p and x

$$\max u(E - p, x; \beta). \tag{4.2}$$

For the buyers the first order condition (FOC) for a maximum is

$$\frac{\partial u(p,x)}{\partial c}\frac{\partial p}{\partial x} - \frac{\partial u(p,x)}{\partial x} = 0, \tag{4.3}$$

Assume for further simplicity a quasilinear utility function which implies a marginal utility of one for non-housing consumption. We obtain

$$\frac{\partial u(p,x)}{\partial x} = \frac{\partial p}{\partial x}. \tag{4.4}$$

Second order conditions (SOC) require $\frac{\partial^2 u(p,x)}{\partial x^2} - \frac{\partial^2 p(x)}{\partial x^2} < 0$. Thus, a buyer will face different marginal prices depending on the chosen x. If tastes differ among buyers, i.e. if β is not degenerate, they will pick up different x and face different marginal prices.[7] Hence, marginal price is endogenous in this model. Assuming invertibility, FOC and SOC further determine the mappings $x = d(z, \varepsilon)$, the quantity of the characteristic demanded by the buyers, and its inverse $\varepsilon = \tilde{d}(x, z)$, which – as with d – is a function implicitly depending on p_x, the marginal hedonic price.

The firms similarly maximize profits $\Pi_k = p_j - C_k(x_j; \gamma_k)$ by setting

$$\frac{\partial C(p,x)}{\partial x} = -\frac{\partial p}{\partial x}. \tag{4.5}$$

Given the SOC $C_{xx} + p_{xx} < 0$ and by the implicit function theorem, we can define a mapping $x = s(y, \nu)$ and its inverse $\nu = \tilde{s}(x, y)$.

In equilibrium, the density of the demanded x must equal the one of the supplied x. For buyers of a given observed type z, the density of demand corresponds to the transformed density of the heterogeneity parameter ε

$$f^D_{x|Z=z}(x, z) = f_\varepsilon(\tilde{d}(x, z)) \det \left| \frac{\partial \tilde{d}(x, z)}{\partial x} \right|, \tag{4.6}$$

[7] If we relax the quasilinear assumption, income differences will similarly affect the choice of x.

while, accordingly, the supply of x for a builder of given type y is

$$f^S_{x|Y=y}(x,y) = f_\nu(\tilde{s}(x,y)) \det \left| \frac{\partial \tilde{s}(x,y)}{\partial x} \right| . \tag{4.7}$$

In equilibrium aggregated demand is equal to aggregated supply at each level of the characteristic x. The equilibrium hedonic price function $p(x)$ must therefore satisfy the following second order differential equation, where the integrals run over all buyers z and builders y

$$\int_Y f_\nu(\tilde{s}(x,y)) \det \left| \frac{\partial \tilde{s}(x,y)}{\partial x} \right| dF_y - \int_Z f_\varepsilon(\tilde{d}(x,z)) \det \left| \frac{\partial \tilde{d}(x,z)}{\partial x} \right| dF_z = 0. \tag{4.8}$$

This equation defines the equilibrium conditions summarizing all aspects of the hedonic model. Solutions of the equation depend on the parameters of the model describing the utility function u, on the technology C and on boundary conditions imposed by economic theory.[8] In other words, as long as regularity conditions hold, the hedonic price function can be expressed as an implicit function of the exogenous characteristics, i.e. $p(x; y, z, \nu, \varepsilon)$. Thus, equations (4.6) to (4.8) establish a correspondence between each buyer (z, ε) and the respective builder (y, ν). It is in this sense that hedonic equilibria are sorting equilibria.

The purpose of structural hedonic analysis being the recovery of the parameters of preferences and technology, it may be tempting to solve equation (4.8) directly. In practice the exact functional forms of the utility and cost functions are not known, nor are the distribution of the builders and buyers' characteristics in the population. The direct approach of solving (4.8) is not feasible, i.e. the parameters must be estimated. This is a difficult task because, as pointed out earlier, with heterogeneity (ε, ν) unobserved by the econometrician, the marginal price of the characteristic x is endogenous: different buyers (i.e. buyers with different (z, ν)) face different marginal prices $p(x)$ because they can choose the level of x. Marginal price and exogenous structural shift variables vary together throughout the sample.

[8] For example, initial conditions may be found by imposing reservation utilities or zero-profit conditions.

The usual cost shifters, e.g. variables that only impact on the profit of the firms but not on demand, are of no use as instruments. They cannot help here in identifying demand because the buyers confronted with the different marginal prices are of different tastes. The desired experiment of presenting a consumer of given tastes with an exogenous shift in marginal price, cannot be implemented (KEANE, 2003).

4.3.2 Choice of Identifying Restrictions

Identification can be achieved through the choice of identifying assumptions. Arguably, these should not rely exclusively on functional form assumptions of the hedonic function. As pointed out by HECKMAN, MATZKIN and NESHEIM (2003a), much of the previous work on the estimation of hedonic models had been geared at developing suitable ways to identify the model *assuming* a marginal price function $\frac{\partial p}{\partial x} = p_x$ linear in the characteristics, i.e. of the type $p_x = \pi_1 + \pi_2 x$. The estimated marginal prices were then regressed against the socioeconomic characteristics of the buyers and/or sellers.[9] The authors prove this approach inadequate. A linear marginal price function results only in the most simple, non-generic case. They illustrate this point by simulating different specifications of the hedonic model and solving for $p(.)$ in equation (4.8) directly. Even slightly non-normal heterogeneity parameters generate nonlinear marginal price functions. In other words, the linearization of the marginal price function is not robust, the hedonic model is generically nonlinear.[10]

In a recent paper, BAJARI and BENKARD (2005) suggest a new approach which does not involve the choice of a linear functional form for the marginal willingness to pay function. In contrast to Rosen's approach, their approach begins by specifying the functional form for the utility function. The choice of a functional form for the utility yields a set of first-order conditions for the optimal choice. These can be then solved for a unique set of preference parameters for each individual.

[9] In other words, the marginal price function was interpreted as a first-order approximation of the true function.

[10] It is important to note that a linearized marginal price function might still be a good approximation of the reality. But as soon as heterogeneity is introduced in the model (for example by allowing preference parameters or technology to differ across consumers and producers), the linear variation of the marginal price function is not sufficient to identify preference parameters, a point made earlier by BROWN and ROSEN (1983)

As pointed out by Bishop and Timmins (2008), the strengths of this approach lie in (i) its admission of any form of preference heterogeneity across households and (ii) its avoidance of the endogeneity problems described above. Its drawback, however, comes in the functional form assumption of the utility that are required to perform the inversion procedure.

4.4 Identification of the Structural Hedonic Model

4.4.1 Treatment of Unobserved Amenities

In this section we describe the approach to recovering preferences in a preference inversion as in Bajari and Benkard (2005). We expand the setting of the precedent section by explicitly accounting for unobserved house characteristics. This is more realistic because, in general, only few attributes of the houses are likely to be recorded in most databases.

Let ξ be a scalar that represents the characteristic observed only by the buyer (or an index thereof). We maintain the assumption that ξ is independent of x.[11] Furthermore we assume that the hedonic price function $p(.)$ is strictly increasing in ξ, meaning that the unobserved component is valuable to consumers. Prices are taken as given by the consumer which supposes that the supply market is competitive. We do not require supply side assumptions because it is the demand that restricts prices, as the supply is taken as given. Matzkin (2003) shows under weak conditions that both the functional form of $p(.)$ and the distribution of ξ are (nonparametrically) identified up to a monotone transformation, meaning that they can be recovered uniquely from the distribution of the observable variables x and the price p. Thus, assuming without loss of generality that a normalization has been made to ξ such that the marginal distribution of ξ is $U[0,1]$, the unobserved component of house j with characteristics x_j and price p_j is given by

$$F_{p|X=x_j}(p_j) = \xi_j.^{12} \tag{4.9}$$

The identification of the hedonic price function is achieved in a single cross-section,

[11] We also relax the earlier assumption that x is a scalar.

[12] See Matzkin (2003), lemma 1, for a proof.

even with unobserved characteristics. The hedonic function can be estimated inverting the precedent relationship

$$p(x_j, e_j) = {F^{-1}}_{p|X=x_j}(e_j). \tag{4.10}$$

Various nonparametric estimation methods can be used in order to estimate ξ. MATZKIN (2003) considers kernel estimators, while BAJARI and BENKARD (2005) use local linear regression (LOADER, 1999). We use the latter method in our empirical work.
The authors assume that locally the hedonic price function p satisfies

$$p_{j^*} = \alpha_{0,j^*} + \sum_k \alpha_{k,j^*} x_{k,j^*} + \xi_{j^*}. \tag{4.11}$$

In this equation, the coefficients α_{j^*} are interpreted as the implicit marginal prices faced by consumer i in choosing a specific house j^* with characteristics (x_{j^*}, ξ_{j^*}). The hedonic price function $p(.)$ is still linear in the characteristics, albeit only locally. The usual global linear (or log-linear) assumption is relaxed. The local marginal prices can be recovered through the minimization of the weighted least squares criterion

$$\sum_{j=1}^{N} W\left(\frac{\|x_j - x_{j^*}\|}{h}\right)(p_{j^*} - (x_j - x_{j^*})'\alpha_{j*})^2, \tag{4.12}$$

where $W(.)$ is a suitable weight function, $\|.\|$ denotes the Euclidian norm and h, the bandwidth, controls the smoothness of the fit. The norm implies that in determining the implicit marginal prices α_{j^*}, the observations near j (in the characteristics' space) of j^* are given a higher weight. The estimates of equation (4.12) allow the recovery of the unobserved characteristic

$$\xi_{j*} = p_{j^*} - x'_{j^*}\hat{\alpha}_{j*}. \tag{4.13}$$

In other words, the residual of the local regression can be directly interpreted as the unobserved characteristic.

4.4.2 Estimation of Preferences

The utility maximization problem stated in equation (4.1) can be reframed to account for the unobserved characteristic ξ. Denote by $u_i(x_j, \xi_j, c)$ the utility of a consumer i representing all consumers (households, buyers) active in the housing market. Typically, only one choice is observed per consumer; the identification of the consumer's preference relation is not possible without additional assumptions. Again, following the formulation of utility given in Bajari and Benkard (2005) and commonly used in microeconometrics, the utility of consumer i purchasing house j is specified as quasilinear, i.e. as log-linear in the housing characteristics and linear in non-housing consumption c, and the unobservable ξ,

$$u(x_j, \xi_j, c_i) = \sum_k \beta_{i,k} \ln(x_{k,j}) + c_i + \xi_j. \tag{4.14}$$

FOC for maximization in the observable characteristics are

$$\beta_{i,k} = \frac{\partial p}{\partial x_{k,j}} x_{k,j},\ \ k = 1, \dots, K. \tag{4.15}$$

The distribution of tastes can thus be recovered using the implicit marginal prices obtained from the local linear (or polynomial) regression. The preference parameter for the characteristic k of a consumer i choosing house j is simply

$$\hat{\beta}_{i,k} = \hat{\alpha}_{k,j} x_{k,j}. \tag{4.16}$$

The cumulative distribution function can be readily estimated by its empirical counterpart

$$\hat{F}(\beta_k = b) = \frac{1}{N} \sum_{i=1}^{N} 1(\hat{\beta}_{i,k} < b). \tag{4.17}$$

Note, however, that the restriction imposed on utility in order to recover preferences in the preceding example implies a constant marginal utility of the characteristic x. On the other side, it is a desirable feature of this model that the MWTP can vary in unrestricted way across individuals. Furthermore, the chosen methodology does not restrict the preference parameters for housing attributes to be independent.

Chapter 5

Demand for Location and Environmental Amenities

5.1 Empirical Application in the Canton of Zurich

In this section we apply the structural hedonic model to a sample of single-family home (SFH) transactions located in the Greater Zurich area. In particular, we recover the MWTP for centrality, i.e. for a location near to the city center and its Central Business District, and for a view on the Lake of Zurich.[1] We then report how the MWTP varies as a function of the owners' socioeconomic characteristics.

The data were obtained from a regional mortgage originator and pertain to SFH sales that took place between 1996 and 2006. The information contained within the data set includes the sale price, date of sale, a rich set of structural attributes and detailed characteristics of the location. Travel distance by car from the city center (defined as Zurich main station) was computed using a GIS-based traffic model. The descriptive statistics of the 4,585 transactions are presented in Table 5.1.

The median selling price is CHF 720,000. Houses are located at an average travel time of 33 minutes from the city center. Detailed income tax statements at the time of purchase are available for a sub-sample of 1,685 households (see

[1]Our estimates recover the preferences of the owner-occupiers of single-family homes in the Canton of Zurich, which corresponds to one-fifth of the population. In order to recover the preferences of the population, data on other property type, e.g. condominium and rental apartment, should also be considered

Table 5.1: *Descriptive statistics of housing attributes.*

Attribute	Median	Mean	Std. dev	VC
Price [1000 CHF]	720	768.0	263.0	0.34
Volume [m^3]	688	724.5	228.8	0.32
Lot size [m^2]	437	510.7	328.1	0.64
Age of building [y]	23	32.6	33.7	1.03
Travel time to CBD [min]	33	32.9	12.0	0.24
Lake distance [m]	5,916	7,588.0	5,992.4	0.79

The table reports median, mean as well as the standard deviation (Std. dev) and the coefficient of variation (VC) for the housing attributes. There are 4,585 observations in the sample.

Table 5.2). The income tax statement contains separated records for the household's head and his/her partner, along with additional socioeconomic traits. It is thus possible to measure the household's income with precision.[2] The median household income of the owner-occupiers is CHF 117,600, which corresponds to a price/income multiplier of around 6.

Table 5.2: *Socioeconomic characteristics of the owner-occupiers.*

Variable	Median	Mean	Std. dev	VC
Household income [1000 CHF]	117,599	126,462	57,150	0.45
Age owner [y]	42.99	41.00	9.10	0.21
Self-employed (dummy)	0.06			
Full-time employed (dummy)	0.92			

The table reports median, mean as well as the standard deviation (Std. dev) and the coefficient of variation (VC) for the socioeconomic attributes of the owner-occupier, recorded at purchase. There are 1,675 observation in the sample.

The strong correlation between house value and income, as evidenced in Figure 5.1, will hardly come as a surprise. There are, however, outliers. For example, some household with very high incomes purchased cheap houses. A possible ex-

[2]The database records the income net of the contributions to social security and other mandatory insurances.

planation – barring data enter errors – is that we cannot exclude that some of the transactions were not made at arm's length. The database may include some transactions where the parties have familial ties. On the other side, some of the purchases are likely to be performed by pensioners with low income but with high wealth.[3]

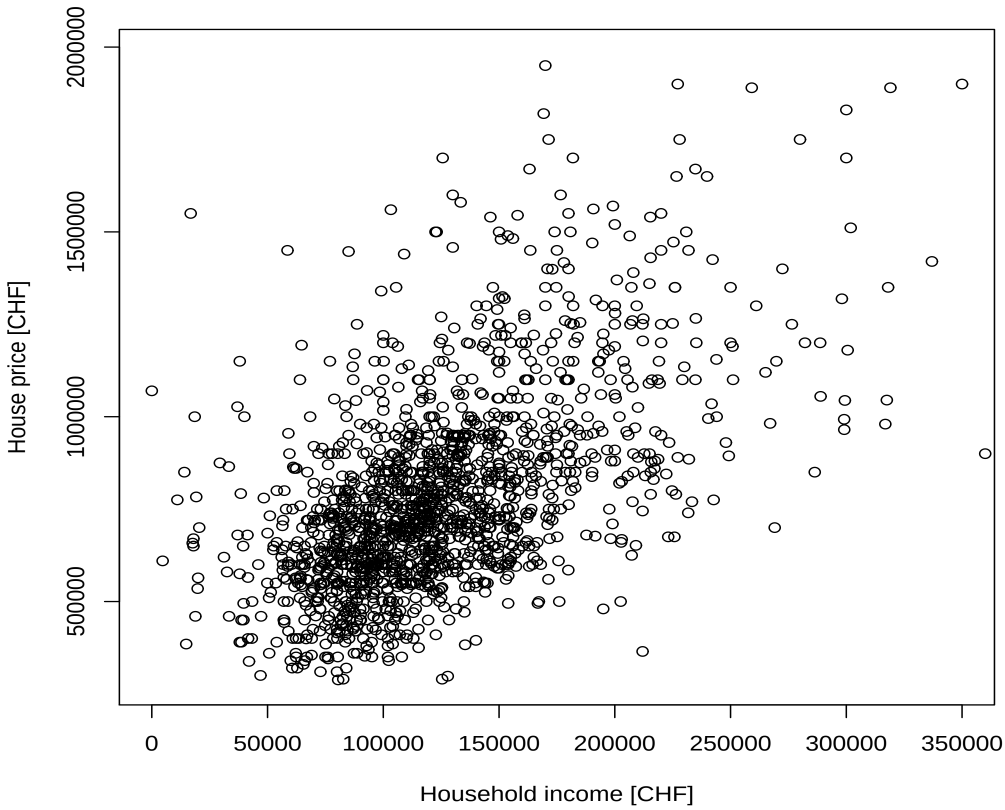


Figure 5.1: *Scatterplot of household income vs single-family house price.*

5.1.1 Local Polynomial Regression Results

The nonparametric estimation of the hedonic function is the starting point in the identification of the hedonic model. Nonparametric methods are subject to the "curse of dimensionality": the convergence of any estimator to the true value of a

[3]Unfortunately, household wealth is not consistently recorded in the database.

smooth function defined on a space of high dimension is notably slow. This means that the number of variables entering the hedonic model should be low, as the number of available observations is not very large. Local polynomial regression is used to estimate the following reduced model containing only the main continuous housing characteristics

$$\ln(p_j) = \alpha_{0,j} + \alpha_{1,j}\ln(\text{VOLUME}) + \alpha_{2,j}\ln(\text{LOT SIZE}) + \alpha_{3,j}\ln(\text{AGE}) + \\ + \alpha_{4,j}\ln(\text{TIME CBD}) + \alpha_{5,j}\ln(\text{DIST LAKE}) + \xi_j, \tag{5.1}$$

where

- p is the sale price in CHF;
- VOLUME is the volume of the house, measured in cubic meters;
- LOT SIZE is the lot size, in square meters;
- AGE is the age of the building, in years, and
- TIME CBD is the travel time to the central business district by car, in minutes.
- DIST LAKE is the distance to the lake of Zurich, in meters.

Table 5.3 summarizes the distribution of the estimated coefficients for these continuous characteristics.[4] With a log-log specification, coefficients can be interpreted as elasticities. As a major departure from the standard hedonic model, we allow for random coefficients, i.e. we allow the MWTP to vary in an unrestricted fashion across individuals. We thus obtain a distinct elasticity for each observation. We do not simply recover an average MWTP from the hedonic price function, as it is standard in the hedonic literature. Hence we are able to describe to which extent preferences vary in the population. As with the usual OLS, the local linear regression fits the data less than perfectly. We interpret the local residual as an estimate of the unobserved attribute, ξ.

[4]Computations were performed in R with the `locfit` package, see R Development Core Team (2006) for details.

Increasing volume by 1% increases the sale price by an average of 0.5%. Notice that this elasticity does not show much individual variation, as signified by the low coefficient of variation of 0.2463. This result suggests that consumers value size quite homogenously. In contrast, the elasticity with respect to the age of the structure has a much more dispersed distribution, with a variation coefficient of the same size as the median estimate. This suggests that consumer's tastes vary greatly with respect to the quality of the structure, as approximated by the age of the building. Although this interpretation can be challenged on the ground that age stands as a proxy for other unobserved relevant choice dimensions (such as the architectural design and the neighborhood characteristics), it is evident that hedonic price elasticities do vary individually.

Table 5.3: *Price elasticity of housing attributes. Summary statistics.*

Attribute	Median	Mean	Std. dev.	VC
Volume	0.5961	0.5938	0.1462	0.2463
Lot size	0.1190	0.1247	0.0645	0.5175
Age of the building	-0.0884	-0.0753	0.0861	-1.1441
Travel time to CBD	-0.2463	-0.2667	0.1167	-0.4377
Lake distance	-0.0395	-0.0350	0.0343	-0.9821

The table reports minimum (Min), first quartile (Q1), median, third quartile (Q3) and maximum values, as well as the standard deviation (Std. dev.) and the coefficient of variation (VC) for the continuous housing attributes. There are 4,585 estimates, one for each available observation.

From these elasticities we can infer $F(\beta_k)$, i.e. the distribution of tastes for housing attribute k in the population. To recover the individual MWTP, the elasticities are combined with the functional form of the utility function as in equation (4.17). The resulting distributions are plotted in Figure 5.2.

All distributions are single-peaked. On average, a one cubic meter increase in size is valued around CHF 500 at the margin. The average building cost oscillated around CHF 550 during the period considered here. Thus, the average marginal valuation for size is roughly equivalent to the building cost. In contrast, owners of SFH seem to attach a low value to a marginal increase of the lot size. The median

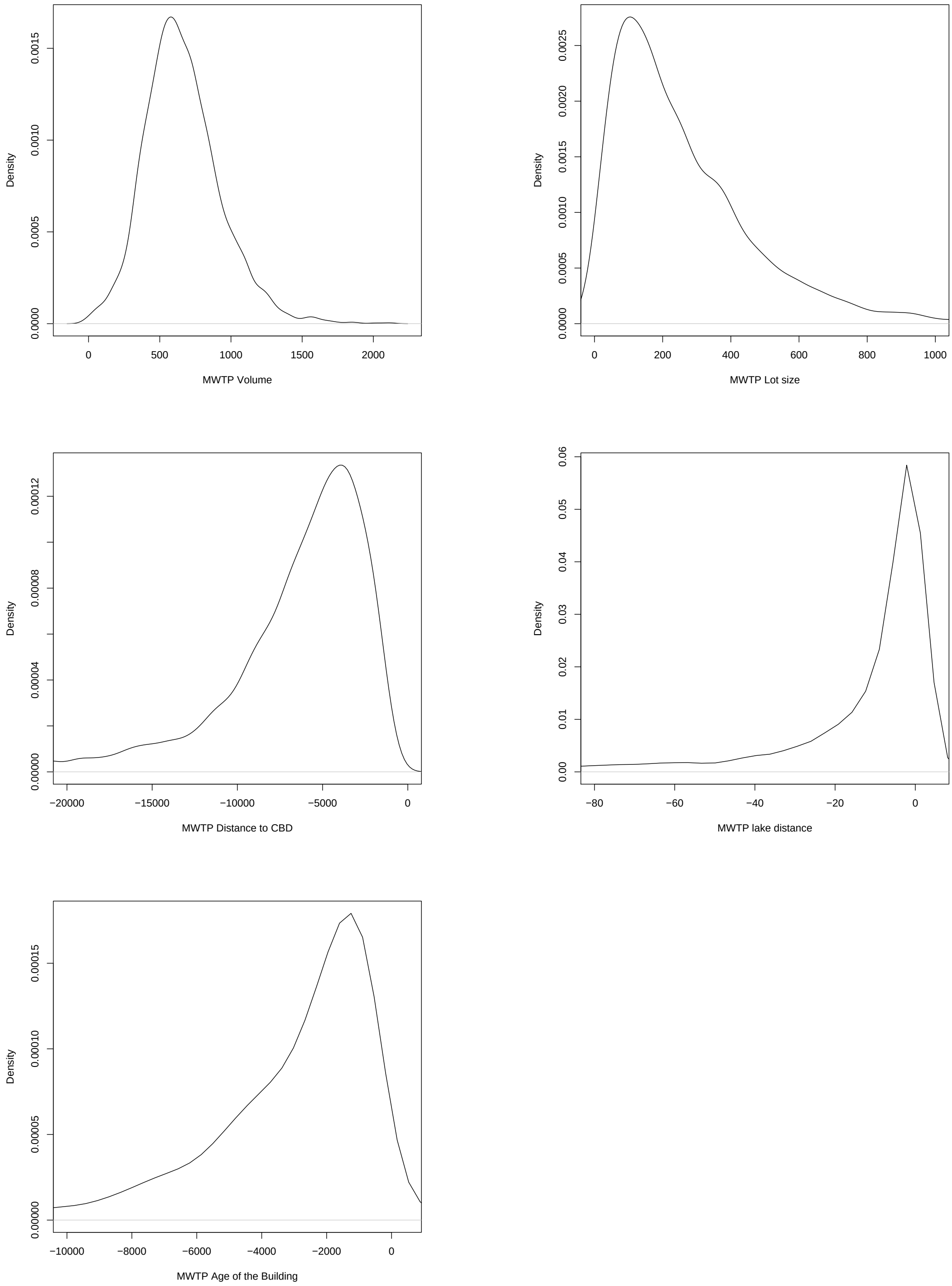


Figure 5.2: *Distribution of the estimated MWTP for the continuous attributes. All MWTP are in CHF per unit of the attribute.*

of the distribution is just over CHF 200 per square meter, which corresponds to less than 30% of the typical average price for unimproved land in the Canton of Zurich. Even the 90% quantile of the MWTP distribution for the lot size (CHF 439) is lower than this average price.[5] Interestingly, this is consistent with the findings of Glaeser and Gyourko (2003) and Glaeser, Gyourko and Saks (2005) who also report low marginal prices for the lot size in densely populated areas in the US. The MWTP for the proximity to Zurich's CBD (i.e. the marginal price of centrality) is visible in the third plot. It peaks around CHF 5,000 per minute of travel time from the city center. However, a sizable part of the home owners in the sample is willing to pay up to CHF 10,000 per minute.

It is important to stress that the chosen methodology does not restrict the preference parameters for the housing attributes to be independent. A look at Table 5.4 reveals that, indeed, there is a significant correlation between the MWTP for the house attributes. For example, we observe a positive correlation between age and travel time to CBD ($\rho = 0.545$). This means that households with an above average MWTP for newer housing tend to value proximity to the CBD the most.

Table 5.4: *Estimated correlations of the MWTP for the housing attributes*

	Volume	Lot size	Age	Travel time	Lake dist.
Volume	1.000	-0.161	0.120	0.044	-0.186
Lot size	-0.161	1.000	-0.548	-0.433	-0.284
Age	0.120	-0.548	1.000	0.545	0.183
Travel time	0.044	-0.433	0.545	1.000	0.170
Lake distance	-0.186	-0.284	0.183	0.170	1.000

Age, travel time to CBD and lake distance have negative marginal prices. Size variables have positive marginal prices. The postive correlation (0.545) between age and travel time to CBD means that households with an above average MWTP for newer housing tend to value proximity to the CBD most.

[5] In 2004 the median transaction price for unimproved land was CHF 552 (Statistisches Amt des Kantons Zürich, 2004).

5.1.2 Impact of Socioeconomic Traits on the Marginal willingness to pay

The buyers' marginal willingness to pay for housing attributes varies as a function of buyer's demographics. We are in the fortunate position to have access to individual level data on the buyers' willingness to pay for each attribute, as well as to precise income tax statements. The income elasticity of owner-occupied housing in our cross-section is about 0.5, meaning that a 1% higher income is associated with the purchase of a house 0.5% more expensive. To explore the impact of demographics we regress the MWTP obtained in the precedent subsection on income, age and on the owner's working status (Table 5.5).

Household income does affect the MWTP for the housing attributes. It exerts the strongest impact on the willingness to pay for proximity to the city center and to the lake. Most of the corresponding coefficients are highly significant, both from a statistical and from an economical point of view. For example, a household with a yearly income between CHF 175,000 and CHF 200,000 is willing to pay 46% more for a marginal decrease in the travel distance to the city center than a household with an income in the CHF 125,000-150,000 bracket.[6] By contrast, the MWTP for size is relatively constant across income classes. Higher income households prefer to invest relatively more in a location that is closer to the center than in a larger house. The impact of income on the MWTP for the lot size is similar in magnitude to the one on the house size. The willingness to pay for age however (as a proxy for the quality of the dwelling) is again strongly income-specific. Further, we notice that the age of the owner has a significant, quadratic impact on the MWTP for the house size, while it has no systematic impact on the demand for the remaining attributes. Whether the home-owner is self-employed or not has little importance for his willingness to pay for housing attributes, with the notable exception of proximity. Arguably, self-employed owners may be more oriented towards the main business and retail center.

[6] $exp(0.8801 - 0.5021) - 1 \approx 0.46$.

Table 5.5: *Marginal willingness to pay for the Housing Characteristics as a Function of Demographic Traits.*

Variable	Size	Lot size	Age	Travel time	Lake distance
Intercept	6.9076 (0.2384)	4.3423 (0.5231)	6.5904 (0.4746)	8.19806 (-0.3098)	2.2927 (1.0799)
Income [CHF]					
75-100,000	0.0112 (0.0418)	0.109 (0.0911)	0.2357 (0.0831)	0.1548 (0.0542)	0.2427 (0.1938)
100-125,000	0.105 (0.0412)	0.3192 (0.0899)	0.5136 (0.0831)	0.3097 (0.0534)	0.5782 (0.1868)
125-150,000	0.1541 (0.0435)	0.4817 (0.0947)	0.7299 (0.0878)	0.5021 (0.0563)	0.7481 (0.1962)
150-175,000	0.1514 (0.0474)	0.7219 (0.1039)	0.9285 (0.0965)	0.6328 (0.0615)	1.0466 (0.2123)
175-200,000	0.1861 (0.0497)	0.7420 (0.1085)	1.1355 (0.0995)	0.8801 (0.0646)	1.7482 (0.2206)
200-225,000	0.2244 (0.0865)	0.8679 (0.1912)	1.3281 (0.1771)	1.1507 (0.1128)	1.6669 (0.3879)
Age owner	-0.0256 (0.0104)	0.0259 (0.0228)	0.0256 (0.0207)	0.0029 (0.0135)	-0.0347 (0.0472)
Age owner^2	0.2531 (0.1104)	-0.3324 (0.2436)	-0.337 (0.2197)	-0.0395 (0.1434)	0.4363 (0.5053)
Self-employed	0.0181 (0.0471)	-0.0924 (0.1021)	-0.0213 (0.0968)	0.1230 (0.0611)	-0.1574 (0.2108)
Full-time empl.	-0.0122 (0.0421)	0.0258 (0.0916)	0.1833 (0.0811)	0.0166 (0.0539)	-0.371 (0.1872)

Regression results with $\ln[MWTP]$ *as the dependent variable. The MWTP for travel time, lake distance and distance enter the regressions in absolute terms. Standard error of the coefficient in parenthesis. An income under CHF 75,000 is taken as the reference class.*

5.1.3 Central Location and Amenities

It is interesting to put the results in the perspective of urban location theories. In the standard monocentric model *à la* Alonso-Mills-Muth, rich households will locate further from the city center if the marginal cost of commuting is less income elastic than housing consumption. This may help to explain why high-income households in the U.S. tend to live in the suburbs, although this explanation has been contested. For example, Wheaton (1977) found that the income elasticity of the demand for land is comparable to the income elasticity of commuting costs. Glaeser, Kahn and Rappaport (2000) similarly argue that it is implausible that the pattern of location can be traced back to differences in marginal commuting cost or housing consumption income elasticity. Outside the U.S., in particular in Europe, the pattern is reversed: rich households tend to live in the city center. Several extensions to the monocentric model have been advanced to explain the different patterns. The work by Brueckner, Thisse and Zenou (1999) is of particularly interest here as it explicitly deals with the impact of amenities on the location of households. The authors show that when the center has a strong amenity advantage over the suburbs, the richer households are likely to live in the center even though their higher housing consumption means that they are more strongly attracted than the poor by low housing prices in the suburbs. In the Zurich region, richer households are segregated in the high amenity locations bordering the Lake of Zurich. In the municipalities on the north-east shore – the aptly called Gold Coast – the mean after-tax disposable income was 56% above the Canton average in 2005.[7] Even in our limited sample, the median distance to the lake of households with income less than CHF 75,000 is about 6.7 km, while for higher income households it is only 4.3 km. The crucial assumption of the amenity-based location theory is that the marginal valuation of amenities rises sharply with income. That this is indeed the case is best seen in Figure 5.3. The MWTP for the proximity to the lake is more than 5.3 times higher in the highest income brackets than in the lowest.

Although these results are suggestive, they are not meant as a formal test of the amenity-based theory of urban location. This is left to future research.

[7]Average income in the municipalities on the shadowy South-East shore were 32% higher than the cantonal average, according to the Statistical Office of the Canton of Zurich

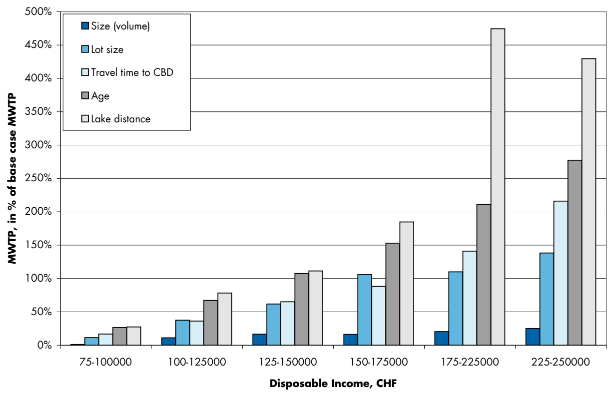


Figure 5.3: *MWTP for housing attributes, relative to the base case (households with income less than CHF 75'000).*

5.2 Conclusion of Part II

Thirty-five years ago, Sherwin Rosen put the hedonic model on the economics' research agenda. Recently, interest in the identification of the demand for differentiated products has been growing. Advances in nonparametric econometrics and a better understanding of the economics underlying the hedonic model have contributed to this renewal of interest. The clarification of the implications of hedonic equilibria and the use of nonlinear identification techniques were pivotal in advancing our understanding of hedonic equilibria. Our work provides one of the first empirical applications of these methods. Its strengths lay in the use of data where both the attributes of the house and the socioeconomic characteristics of the owner-occupier are observed. Based on the estimated MWTP for location attributes presented here, alternative explanations for the different patterns of location in a urban area can be explicitly tested.

Part III

Capital-Land Substitution Elasticity

Chapter 6

The Economics of Capital-Land Substitution

6.1 Introduction

Basic economic insight suggests that high land prices relative to construction prices induce a substitution of the relatively expensive production factor towards the cheaper one. Good knowledge of this mechanism is key to the understanding of much discussed urban phenomena like urban sprawl, the influence of housing prices on urban density or the effect of property taxes on the supply of housing. As such, it may be of interest to urban planners, real estate developers and to the general public alike. If, for example, substitution is easy, rising land prices will induce a sharp increase in the capital intensity per land area, i.e. real estate developers will build more "structure" per square meter of land. Dwellings will have a higher proportion of non-land input (i.e. improvements) and building density will rise. If this is the case, the increase in rents and housing prices caused by the exogenous land price increase will be moderate. Thus, a policy aiming at restricting the supply of open spaces and limiting the availability of unimproved land will have a different impact on housing prices depending on the substitution elasticity. On the other hand, a high value for the substitution elasticity will imply that where land is relatively abundant and housing prices are moderate, the building density will be low and houses will be placed on large lots.

This work is motivated by two general considerations. Although several urban economists have tackled the measurement of the substitution elasticity, most have dealt with the case of U.S. metropolitan areas.[1] However, the urban structure of U.S. cities differs markedly from the one of their counterparts in other regions of the world. Witness, for example, the large differences in the price elasticity of residential housing supply in the United Kingdom compared to the U.S reported in Malpezzi and Maclennan (2001). Furthermore, the literature has not yet reached a consensus on the value of the substitution elasticity in urban areas. Most of the studies surveyed in McDonald (1981) report estimates of a substitution elasticity significantly less than one. However, a more recent and widely cited paper by Thorsnes (1997) argues for a higher substitution elasticity, not significantly different from one. Similarly, Epple, Gordon and Sieg (2006) find that housing supply in the Pittsburgh area reacts elastically to changes in land prices. Applying a new non-parametric technique, they are able to recover the production function of housing from the supply of housing per unit of land. Their findings imply an elasticity of substitution slightly less than one.

The new availability of disaggregated geocoded data for land and housing transactions in the Canton of Zurich, Switzerland's most populous area, creates the opportunity to expand this important strand of the urban economics literature. This part of the dissertation is organised as follows. The following section is devoted to a short recapitulation of the classic housing production theory. A particular focus is given to the derivation of the substitution elasticity. Chapter 7 presents the data and the modelling strategy used in the empirical work. We then go on to report the estimated production functions and discuss the results.

6.2 The Model

6.2.1 The Residential Housing Production Function

In a typical housing production function, the output – the quantity q of housing services – is related to the quantities of land (L) and non-land inputs (K) through the production function $q = H(K, L)$. That is, households are assumed

[1] To the best of our knowledge, the only non-U.S. references are Erol and Guzel (2006) and Dowall and Treffeisen (1991).

to consume an aggregate homogenous commodity, the "housing services".[2] Under this assumption, a larger house with a view on a lake differs from a smaller unit without view only in the quantity of the housing services commodity it delivers. Thus, an increase in the use of capital is not necessarily associated with larger buildings. It can also translate in an increase of the quality of housing supplied, and consequently in an increase of the quantity of housing services. The developer solves the following optimization problem,

$$\max_{K,L} \pi(K, L) = p_H H(K, L) - p_L L - p_K K, \tag{6.1}$$

where $\pi(K, L)$ denotes the profit function. We posit that the production function is strictly increasing in each of its arguments and strictly concave. The factor prices, p_L, p_K, and the price of housing p_H are taken as given. We first sketch the solution of this maximization problem for the well-known case of a CES production function

$$q = A[\delta K^\rho + (1 - \delta)L^\rho]^{1/\rho}. \tag{6.2}$$

First-order conditions are

$$-p_K + p_H A[\delta K^\rho + (1 - \delta)L^\rho]^{(1-\rho/\rho)} \rho\delta K^{\rho-1} = 0 \tag{6.3}$$

and

$$-p_L + p_H A[\delta K^\rho + (1 - \delta)L^\rho]^{(1-\rho)/\rho} \rho(1 - \delta)L^{(\rho-1)} = 0 \quad . \tag{6.4}$$

Dividing the second condition by the first we obtain

$$\frac{p_L}{p_K} = \frac{1 - \delta}{\delta} \left(\frac{K}{L}\right)^{-1/(\rho-1)} \quad . \tag{6.5}$$

Given the highly fragmented structure of the construction industry, one can realistically assume constant returns to scale in housing production. The marginal factor productivity is thus independent from the level of production, with devel-

[2]As such housing services is a flow, i.e. it has a time dimension. However, for simplicity, we neglect this time dimension by assuming a fixed discount rate for all housing units. This allows us to work with housing prices, as opposed to imputed annual rents.

opers choosing a given capital intensity $S = K/L$,

$$q(K,L) = L \cdot H(K/L,1) = L \cdot H(S). \tag{6.6}$$

For the useful special case of the Cobb-Douglas function with constant returns to scale

$$q = AK^{\delta}L^{1-\delta} = L \cdot AS^{\delta}, \tag{6.7}$$

with $A > 0$ and $0 < \delta < 1$. The first-order condition for a maximum is simply

$$\frac{K}{L} = \frac{\delta}{1-\delta}\frac{p_L}{p_K}. \tag{6.8}$$

In this case, factor shares are independent of the factor prices, i.e. an exogenous increase in the price of land is matched by a proportional decrease of the quantity of land used. Thus the developer's rule-of-thumb which states that the value of the structure should be about twice the value of the land, implies $\delta = 2/3$. Finally, some researchers have estimated the parameters of a variable elasticity of substitution production function. One possible choice is given by Revankar's VES production function (Revankar, 1971), used in this context by Sirmans, Kau and Lee (1979), where

$$q = \gamma L^{\alpha(1-\delta\rho)}\left[K + (\rho - 1)L\right]^{\alpha\delta\rho} \tag{6.9}$$

with $\gamma > 0, \alpha > 0, 0 < \delta < 1, 0 \leqslant \delta\rho \leqslant 1$, and $K/L > (1-\rho)/(1-\delta\rho)$. Under constant returns to scale, $\alpha = 1$. The developer's first-order conditions for this production function imply

$$\frac{p_L}{p_K} = \left(\frac{K}{L} - \frac{1-\rho}{1-\delta\rho}\right)\left(\frac{1-\delta\rho}{\delta\rho}\right). \tag{6.10}$$

6.2.2 Factor Substitution in Housing Production

One of the tenet of marginalism is the substitution in production, i.e. the idea that a decrease in the utilization of one input factor can be compensated – or substituted – by the increase in the use of another input to maintain the same output level. Consider again the housing production function $q = H(K,L)$. Under standard regularity conditions, the total differential of this production function is $dq = H'_K dK + H'_L dL$. For movements along an isoquant, $dq = 0$. Hence

$$\frac{dL}{dK} = -\frac{H'_K}{H'_L}. \tag{6.11}$$

The change in the input ratio has to compensate the ratio of the marginal products. This ratio is called the (marginal) rate of technical substitution (MRTS). Typically, isoquants are convex. They exhibit diminishing rates of technical substitution, meaning that it becomes increasingly difficult to substitute an input for another. The elasticity of substitution measures the degree of ease with which this substitution can be made. It is an unit-free measure of substituability between factor inputs defined as

$$\sigma = -\frac{\partial ln\left(\frac{K}{L}\right)}{\partial ln\left(\frac{H'_K}{H'_L}\right)}. \tag{6.12}$$

Thus, the elasticity of substitution σ measures the percentage change in the factor input proportion K/L following a change in the marginal rate of technical substitution. In a Leontief technology production factors are used in fixed proportion. A change in MRTS will not lead to any change in the factor proportion, i.e. $\sigma = 0$. In the polar case of perfect substitution, i.e. with a linear production technology, the MRTS is constant for any factor mix. Consequently, $\sigma = \infty$. An interesting special case is again given by the Cobb-Douglas production function. From its definition it readily follows that $H'_K = \delta q/K$ and $H'_L = (1-\delta)q/L$. The elasticity of substitution is then

$$\sigma = \frac{1-\delta}{\delta}\left[\frac{\delta}{1-\delta}\frac{K}{L}\right]\frac{L}{K} = 1. \tag{6.13}$$

A 1% change in the MRTS causes a 1% change in the input mix. In the more general case of the CES production function with constant return to scale, given in (6.2), it can be shown that the elasticity of substitution is $\sigma = 1/(1+\rho)$. In the case of the VES production function in (6.9), it is equal to

$$\sigma = \frac{\delta\rho}{1-\delta\rho}\frac{p_L/p_K}{K/L}. \tag{6.14}$$

The elasticity of substitution may vary with the factor mix. With competitive input factor markets, first-order conditions for the maximization of the profits imply that the ratio of marginal products is equal to the relative prices. In this case, we have

$$\sigma = -\frac{\partial ln\left(\frac{K}{L}\right)}{\partial ln\left(\frac{p_K}{p_L}\right)}. \tag{6.15}$$

Thus, following a 1% decrease in the (relative) price of capital, the use of capital is increased by σ% for a site of given size.

The elasticity of substitution can also be written in terms of the cost function $C(p_K, p_L, q)$, the minimal value of the total cost as a function of the unit cost of each factor and the quantity of housing services. It can be shown that

$$\sigma = \frac{CC_{p_K p_L}}{C_{p_K} C_{p_L}}, \tag{6.16}$$

where C_{p_K} and C_{p_L} designate the partial derivatives of the cost function with respect to the factor prices.[3] Further, knowing that $\eta^L_{p_K}$, the cross elasticity of the (conditional) land demand with respect to the price of capital is equal to $(K/L)C_{p_K p_L}$, the expression (6.16) leads to $\eta^L_{p_K} = (p_K C_{p_K} C_{p_L}/LC)\sigma$. Since, by Shephard's lemma, $L = C_{p_L}$ and $K = C_{p_K}$, it follows that $\eta^L_{p_K} = (1-s)\sigma$, where $s_L = p_L L/C$ is the land share in the total cost. The demand for land depending only on the ratio (K/L), we have $L_{p_L} = -(p_K/p_L)L_{p_K}$. Hence

$$\eta^L_{p_L} = -\eta^L_{p_K} = -(1-s_L)\sigma, \tag{6.17}$$

Accordingly, for a given capital stock, an exogenous increase in land prices will have a stronger impact on the derived demand for land when the substitution elasticity is high or the share of land is small.[4] We use these relationships when we discuss the empirical results.

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[3]See Cahuc and Zylberberg (2004, Ch. 4.1) for the detailed derivation of this and the following results

[4]Note that in the Cobb-Douglas case the elasticity of land demand is simply $\eta^L_{p_L} = -\delta$.

6.2.3 Model specification

Housing services is a composite, unobservable commodity: the price of a housing services unit, p_H, and its quantity q cannot be observed separately. However, we do observe their product, $p_H q$, i.e. the value of housing. Moreover, when the value of the land $p_L L$ is known, we can infer the value of the structure, $p_K K$. Let v be the value of the structure per unit of land, $v = p_K K/L$. For the case of the CES production function, it follows from the first-order conditions of the developer's maximization problem in (6.5) and from the definition of the elasticity of substitution that

$$\frac{p_L}{p_K} = \frac{1-\delta}{\delta}\left(\frac{K}{L}\right)^{1/\sigma} \quad . \tag{6.18}$$

Taking logs and adding $\ln p_K$ on both sides gives

$$\ln v = c + \sigma \ln p_L + (1-\sigma)\ln p_K, \tag{6.19}$$

where c is a constant. Note that, usually, the price of capital (i.e. non-land inputs) is assumed as constant in the cross-section. Consequently, the third term in (6.19) can be dropped. For the special case of the Cobb-Douglas production function this simplifies further to

$$\ln v = c + \ln(p_L). \tag{6.20}$$

In the case of the VES production function, first-order conditions imply

$$v = \frac{1-\rho}{1-\delta\rho} + \frac{\delta\rho}{1-\delta\rho} p_L. \tag{6.21}$$

These equations are stated in terms of observable quantities. They can be estimated given suitable data on land and housing transactions.

Chapter 7

Estimation of the Substitution Elasticity

7.1 Description of the Data

The empirical part of this paper relies on two distinct data sources which we here describe. The first data set contains details of 4,941 arm's length transactions of residential land in the Canton of Zurich which occurred between 1995 and 2006. The data is provided by the Statistical Office of the Canton of Zurich and is collected by notaries and land-registry offices.[1] Each parcel of land is geocoded and matched to the attributes of the location described in Table 7.1.

The median price per square meter of land in current prices is 601 CHF per square meter. There is a large variation in residential land prices with the first decile equal to roughly a tenth of the last decile. The geographic attributes include measures of accessibility (travel time to Zurich CBD by car), environmental amenities (view, steepness of the terrain) and a measure of local nuisance (road traffic noise).[2] With the help of a digital terrain model, the extent of the view on two major amenities – the lakes in the Canton of Zurich and the Swiss Alps –

[1] The original database contains all land transactions that occurred in the Canton of Zurich. From this original file, we discarded transactions of land zoned for agricultural, commercial or industrial use. Transactions that were not at arm's length or could not be precisely located were also deleted from the database.

[2] Travel time to Zurich CBD is computed from 674 travel zones, spanning the Canton of Zurich. It measures the mean travel time during week-day morning hours in order to better reflect the accessibility of the central city to commuters.

Table 7.1: *Descriptive Statistics of the Land Transactions*

Variable	Min	Max	Median	Mean	Std. Dev
Price [CHF/m^2]	78.2	2,796.0	601.1	650.1	273.0
Lot size [m^2]	151.0	4,932.0	487.0	597.3	441.1
Travel time to CBD [min]	18.0	55.0	37.0	33.0	7.3
Slope terrain [%]	0.1	21.6	5.8	6.1	3.4
View on lakes [ha]	0.0	6,970.0	0.0	556.9	1,303.4
General view [ha]	9.0	95,808.0	17,291.5	19,334.0	12.875.9
Near power line (<200m)	0.0	1.0	0.0	0.1	0.1
Distance from major roads [m]	0.0	4,204.0	352.1	507.5	487.2

The location variables were matched at the lot level for each of the 4,941 unimproved land transactions zoned for single-family homes, sold in the Canton of Zurich between 1995 and 2006. The distance to CBD is measured as the car travel time to Zurich Main station. View variables were computed at an height of 4 meters above ground.

were simulated for each of the 54,000 built hectares in the Canton of Zurich and matched to the land plot data. In addition to these location variables we have access to the official location rating of the Cantonal tax authority. In 1996, the tax authority established a ranking of each neighborhood in the Canton of Zurich. This involved an *in situ* inspection by independent assessors of all neighborhoods in the Canton and their subsequent ranking on a 5-point scale. The ranking compares the quality of a location with respect to the other locations in the same municipality. Several amenities were considered when the ranking was drafted. Among them traffic noise and other noise exposure; exposition to the sun, view and topography; proximity to schools, shops, parks and cinemas; accessibility by car, by public transportation, parking space and the image of the neighborhood.

A second data set is provided by a regional mortgage originator. It records 4,229 transactions of single-family homes in the Canton of Zurich. These transactions occurred between 1995 and 2007. In addition to the transaction prices, the records contain detailed information describing key features of each house, such as the lot size, volume, number of rooms, age and several other structural characteristics listed in Table 7.2, along with their respective descriptive statistics.

The summary statistics of the house transactions are close to the corresponding statistics of the land lots listed in Table 7.1. This reflects the good representative-

Table 7.2: *Descriptive Statistics of the Main House Characteristics*

Variable	Min	Max	Median	Mean	Std. Dev
Price [1000CHF]	200	2,880	720	769.0	271.5
Lot size [m^2]	100	2,715	430	501.9	321.0
Age of building [y]	1	156	22	31.4	33.5
Travel time to CBD [min]	12	56	33	32.8	8.0
View on lakes [ha]	0	6,970	0	517.1	1,249.4
General view [ha]	163	98,648	16,650	18,415.3	12,778.1
Road traffic noise, Lr 16h [dB]	0	18.5	0	0.8	2.6
Near power line (if <200m)	-	-	-	0.023	-
Distance from major roads [m]	1	4'055	269	430.9	478.0

The location variables were matched at the hectare level for each of the 4,229 single-family homes transactions, sold in the Canton of Zurich between 1995 and 2006. Location variables are defined as with the land transactions. Of the 4,229 transactions, 35.4% are new constructions while the other are resales.

ness of the housing transactions data. For example, the mean travel time to the CBD is 32.8 minutes, 0.2 minute less than for the land transactions. The mean value of houses (single familiy homes) per square meter of land is CHF 2,011. Note that about one third of the transactions are of newly built houses with less than 2 years of age.

7.2 Empirical Results

7.2.1 Estimation of the Hedonic Land Price Model

Unfortunately, due to limitations in our land and housing transaction databases, we cannot match land transactions with the subsequent house sales. In other words, it is not possible to track the development process from the acquisition of the parcel to its completion, i.e. the sale to the owner-occupier. In order to gather further information useful for the estimation of the production function, we have to combine the two data sources in an indirect way. We thus first estimate a hedonic model of the unimproved land. This model is used to predict the land prices of the houses for which detailed transaction data is available. In fact, we use the prediction of the hedonic model as if they were the actual land prices paid by the developers or the home buyers.[3] In a second step, we use the generated lot prices to calculate the value of non-land inputs. We then proceed to the estimation of the production functions along the lines described in the model section.[4] Table 7.3 displays the results of regressing the log land price on the plot characteristics. We give the results of two basic specifications. The first one reported on the left side of Table 7.3 contains both municipality fixed-effects and the tax authority location assessment. It is thus more useful for predictions, as it does not attempt to explain the location attractiveness. The second model, reported on the right side of the table, does not contain fixed-effects. It is thus more apt at revealing the impact of the amenities on land prices.

Both model performs quite well in explaining the large variation in land prices across the Canton of Zurich. Unsurprisingly, the predictive model fits the data best, reflecting the fact that municipality indicator variables capture a large part of the land price variance. This partly reflects the importance of local government in federalistic Switzerland, where income tax rates are set to a large extent at the level of the municipality. The tax-authority ranking of the location is also highly significant. Nonetheless, some of the GIS location variables maintain their significance. This model achieves the highest fit, with an R^2 statistic of 0.756 and a residual standard error of 0.183.[5] The coefficient of the log lot size (-0.046) is significantly less than zero implying a moderate discount for larger lots. By this account, an increase of the lot size of 10% reduces the per square meter price of the lot by about half a percent.

[3]From en econometric point of view, we have to account for the fact that land prices are estimates. In a OLS estimation with generated regressors, parameter estimates are still unbiased, but standard errors and t-statistics are generally invalid (Wooldridge, 2002, Ch. 6).

[4]Some older papers (e.g. Clapp, 1980; Jackson, Johnson and Kaserman, 1984) directly use a hedonic model of housing transactions to infer implicit land prices. Under conditions described in Heckman, Matzkin and Nesheim (2003b), the implicit hedonic price reflects in equilibrium the marginal valuation of consumers for comparable houses situated on lots of different sizes. However, as pointed out by Glaeser and Gyourko (2003), the homeowners' valuation of the lot size implied by hedonic price models is often much lower than the corresponding land price. This is puzzling, since in principle a homeowner who does not value the land on his plot very much would subdivide and sell it to someone else. At the present moment, the reasons for this large difference are still open to debate (O'Flaherty, 2003). At the very least, caution is advised when using implicit hedonic prices to assess the value of unimproved land.

[5]Note that the dependent variable is the price per square meter of land. The same model with the lot price as dependent variable achieves an adjusted R^2 of 0.92.

Table 7.3: *Land Hedonic Regression*

	"Predictive" Model			"Structural Model		
Variable	Estimate	Std. Error	t-Value	Estimate	Std. Error	t-Value
Intercept	7.842	0.184	42.64	9.281	0.083	105.10
Log travel time to CBD	-0.108	0.070	-1.54	-0.871	0.020	-43.11
Log lot size	-0.046	0.007	-6.47	-0.001	0.008	-0.09
Slope terrain $3-9\%$	0.008	0.008	0.94	0.037	0.009	4.00
Slope terrain $> 9\%$	-0.001	0.010	-0.14	0.048	0.011	4.31
Lake view 0-20 km^2	-0.026	0.015	-1.70	0.215	0.011	20.21
Lake view 20-40 km^2	0.013	0.025	0.52	0.378	0.015	24.79
Lake view >40 km^2	0.018	0.035	0.52	0.301	0.020	14.93
View 50-100 km^2	0.041	0.014	2.91	0.109	0.016	6.83
View 100-250 km^2	0.025	0.015	1.69	0.066	0.013	5.03
View >250 km^2	0.044	0.018	0.52	-0.076	0.015	-5.23
Near power line	-0.002	0.022	-0.11	0.020	0.026	0.76
Distance to major road [km]	-0.013	0.024	-0.56	0.239	0.018	13.10
Distance to road squared	0.003	0.012	0.26	-0.098	0.007	-13.54
Location assessment (compared to "best")						
"Good"	-0.065	0.009	-7.36			
"Average"	-0.107	0.011	-9.74			
"Modest"	-0.194	0.017	-11.09			
"Poor"	-0.310	0.027	-11.38			
Residual standard error	0.183			0.279		
Adjusted R-squared	0.755			0.459		
Number of observations	3,918			4,939		

The dependent variable is the log land price per square meter. We report the estimates of two hedonic regressions. The first, labelled "Predictive Model", with municipality fixed-effects and the assessments of the location by the tax authority. The second model ("Structural model") does not contain fixed-effects nor the location assessments. The estimates for the municipality and the time fixed-effects are not shown in this table. They are available from the author upon request. The location variables were matched at the lot level for each of 4,939 unbuilt land transactions, sold in the Canton of Zurich between 1995 and 2006, located in single-family homes building zones. Due to missing data in the location assessment variable, only 3,918 observations can be used in the predictive model.

The alternative model without fixed effects is more interesting from an economic point of view. Reflecting Zurich's broadly monocentric urban structure, the distance from Zurich's CBD has a large impact on land prices. An increase from 33 to 34 minutes of the travel time knocks-off about 17 CHF from the square meter price of land. The other location variables have also a significant impact on land prices, both in statistical and economical terms.

7.2.2 Estimation of the Non-land Inputs

The land price regression results are now used to estimate the implicit value of the plot in the sample of house sales. We compute the value of the house structure by subtracting the estimated land value from the observed transaction price. As in Epple, Gordon and Sieg (2006), we want to verify whether the estimated value of the non-land input is correlated to the observed structural attributes of the houses.[6] From an economic point of view, this makes only sense for new housing. The land transaction used in the land price hedonic model are of plots ready to be developed. To apply the same land value to older housing is arbitrary from the perspective of the economic interpretation of land value, where land is viewed as deriving its value solely from the development or redevelopment right it confers on its owner. Thus, we limit the sample of the house transactions to new dwellings (at the time of the sale), and estimate their structural value. The results of a OLS regression of the value of the house structure on the house characteristics of new houses are shown in Table 7.4.

There is a comfortable degree of correlation between the value of the structure and the house characteristics. The adjusted R^2 is 0.56. In accordance with the residual land value theory, the value of the location should be attached to the land value, not to the value of the structure. Hence, if the land prices have been correctly estimated, the value of the structure should not vary significantly across municipalities. To verify this hypothesis we include municipality fixed-effects in the hedonic regression of the structure. Only 6 out of 125 municipality fixed-effects

[6] Epple, Gordon and Sieg (2006) do not directly observe the price of land. Instead, they use the tax authority's assessment as a proxy for the land value. To that extent, they face a similar problem as in our study.

Table 7.4: *Hedonic Model of the House Structure Price*

Variable	Estimate	Std. Deviation	t-Value
Intercept	9.708	0.180	54.03
Age of building	-0.011	0.001	-12.88
Age squared	0.005	0.001	9.44
New	0.224	0.034	6.43
Renovated	0.338	0.029	11.52
Well maintained	0.210	0.020	8.33
Brick building	0.060	0.027	2.17
Cellar	0.071	0.030	2.35
Double glazing	0.088	0.016	5.28
Floor heating	0.074	0.018	4.03
Garage	0.033	0.016	2.08
Underground garage	0.07	0.019	3.65
Modern kitchen	0.099	0.015	6.46
Swimming pool	0.056	0.043	1.32
Sauna	0.097	0.033	2.94
Log size [m^3]	0.379	0.027	13.75
Log rooms	0.151	0.037	4.06
Log bathrooms	0.177	0.022	7.74
Residual standard error	0.323		
Adjusted R-squared	0.561		
Number of observations	4,060		

The dependent variable is the log house price minus the estimated land price. Municipality and time fixed-effects were included. Only 6 out of 123 fixed effects were significantly different from zero at a marginal probability level less than 5%.

are significant at the 5% level.[7]. This is reassuring and – considering the good fit of the hedonic land model – gives us confidence in the quality of our estimated land values.

Figure 7.1 shows the empirical distribution of v, the value of the house structure per unit of land for both new and older housing. The median value is 1,860 CHF/m^2 (in current prices) for newly built housing and 730 CHF/m^2 for older

[7] For reasons of space, we do not report the detail of the estimated fixed-effects in Table 7.4. They are available from the author upon request

houses. We use this quantity as the dependent variable in the following estimation of the substitution elasticity.

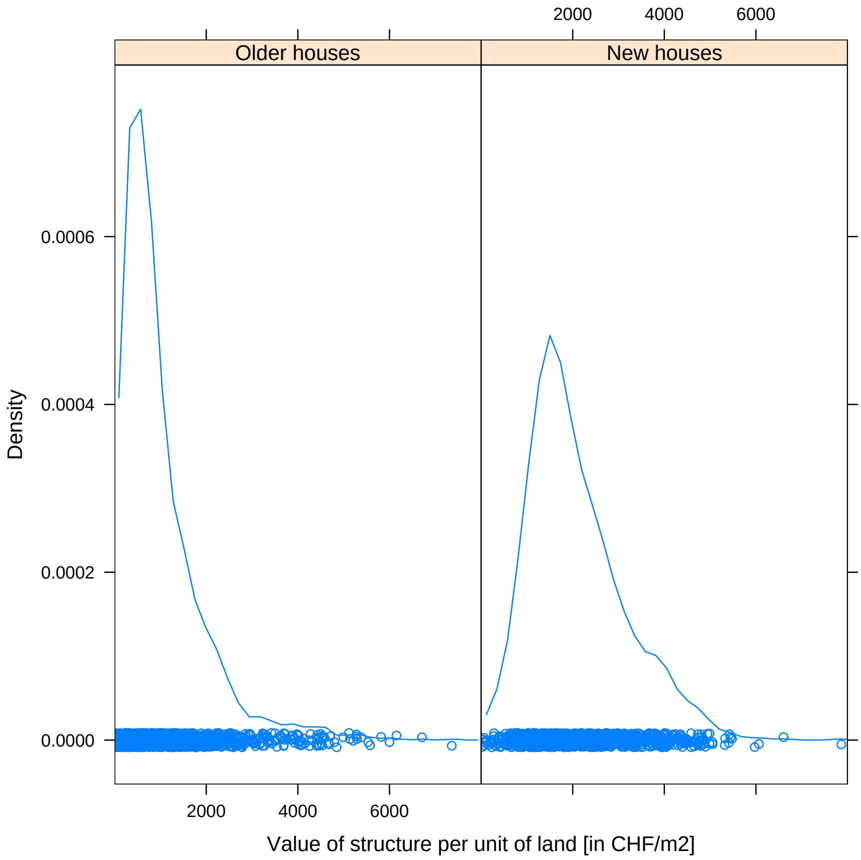

Figure 7.1: *Value of the house structure per unit of land (v). The right panel shows the density plot of v for new single-family homes, measured in Swiss Francs per square meter of lot size. On the left the corresponding density for older houses.*

7.2.3 Land Shares

Notwithstanding the previous discussion, it is interesting to compute the land share (by the appraisal definition of the term), even for older properties. Figure 7.2.3 shows the distribution of the land shares for different vintages.

The bottom left panel reports the estimated land shares for new housing, with older vintages reported in the upper panels. Land shares for new single-family

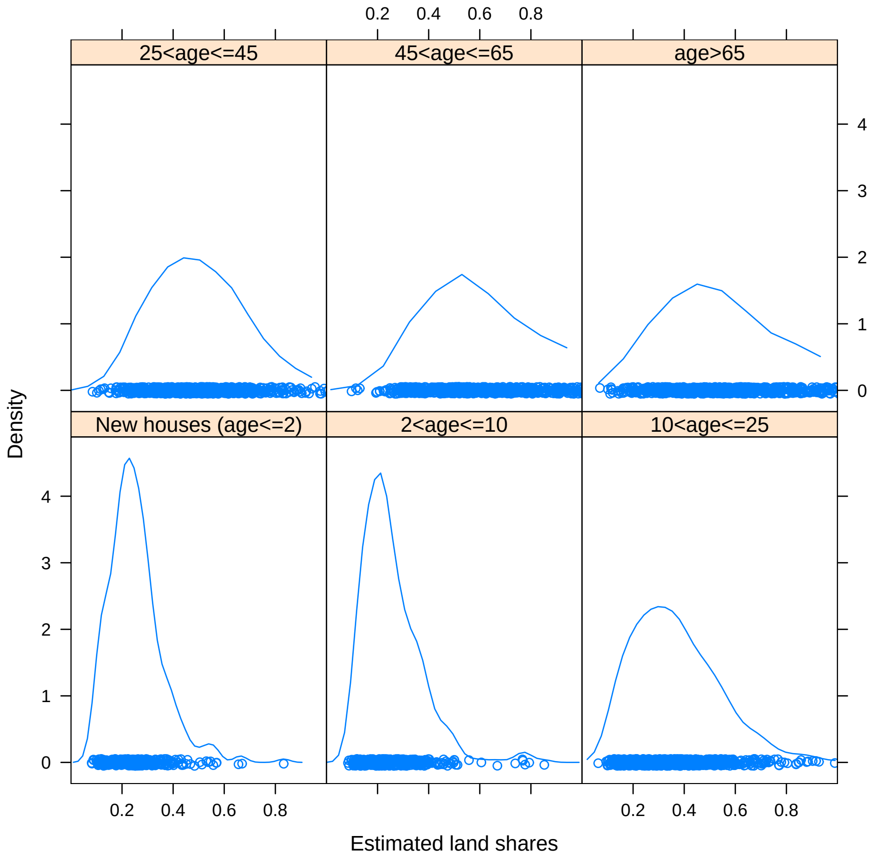

Figure 7.2: *Density of Estimated Land Shares for Different House Vintages.*

homes are in the 20%-30% range, the median land share being 23.8%. Older houses have a much higher land share, often in excess of 50%, reflecting the value of the redevelopment option.[8] The dispersion of the shares is larger for older vintages. This is partly due to the fact that some of the houses are likely to have been been renovated and improved, i.e. the redevelopment option has been partly exercised. On the other hand, changes in land prices since construction may have differed across locations. Summing up, the distribution of land shares is consistent with the view that, at the time of construction, developers do adjust to the the cost of the land. The extent of this adjustment is the focus of the next section.

[8]For example, the median land shares of the houses older than 65 years is 53%.

7.2.4 Estimation of the Elasticity of Substitution

We now turn to the main goal of this part, the estimation of the substitution elasticity. Table 7.5 reports the results for σ obtained with the CES and VES specifications of the equations 6.19 and 6.21. Recall that the land prices on the right hand side of the regression equation are generated by a previous estimation. We thus additionally report suitably adjusted standard errors.[9]

Table 7.5: *Estimate of the Substitution Elasticity with CES and VES Production Functions*

	CES			VES		
Variable	Estimate	SE	Adj. SE	Estimate	SE	Adj. SE
Intercept	3.594	0.282	0.277	832.226	92.994	112.7
ln Land price	0.6178	0.043	0.038	2.013	0.147	0.194
SER	0.405			863		
R2	0.134			0.130		
N	1,257			1,257		

In the VES (CES) case, the dependent variable is the (log of) value of non-land factor input per square meter of land, v. Both adjusted and unadjusted standard errors (respectively Adj. SE and SE) are reported. Adjusted standard errors control for generated regressor bias. The sample consists of 1,257 new houses.

In the CES specification, the dependent variable is the log value v of the non-land input per square meter of land. The regression results show that in the CES case, the elasticity of substitution is 0.617. This is significantly lower than one, both from a statistical and economical point of view. Our data thus strongly rejects the Cobb-Douglas specification. For the VES case, the substitution elasticity varies along the expansion rays and the estimated parameter must be multiplied with the capital/land-ratio, as shown in Section 6.2. This results in a low median elasticity of substitution of $\sigma = 0.553$, with an interquartile range between 0.410 and 0.676. Thus, both specifications suggest that in the Canton of Zurich capital/land substitution is quite limited.

We perform some specification checks to validate our estimation strategy. In the

[9]See WOOLDRIDGE (2002, p. 139) for details on the adjustment method.

CES case we assume log-linearity. We thus run two linearity tests for the CES specification, a Rainbow test and a RESET test. The basic idea of the Rainbow test is that even if the true relationship is non-linear, a good linear fit can be achieved on a subsample in the "middle" of the data. The null hypothesis is rejected whenever the overall fit is significantly worse than the fit for the subsample. The RESET test is another popular diagnostic for correctness of functional form. Both tests fail to reject the null at the usual level of significance (p-value of 0.57 for the Rainbow test, 0.85 for the RESET test with residuals up to the third power). We also interact the land price variable with time dummies to assess the stability of the regression. All parameters are within 2% of the base case CES estimate. Our findings are consistent with earlier studies on the elasticity of substitution. McDonald (1981) reports estimates for σ between 0.36 and 1.13. However, they are lower than the more recent results of Thorsnes (1997) and Epple, Gordon and Sieg (2006). As noted in in Section 6.2, the substitution elasticity can be combined with the factor shares in order to yield estimates of the own-price elasticity of the (conditional) factor demands. The reaction of the demand for land to changes in prices will be higher when the share of land is low or when the elasticity of substitution is high. Given the CES estimate and a mean land share for the new houses of $s_L = 0.238$, the price elasticity of the demand for land is $\eta^L_{p_L} = -(1 - 0.238)0.617 = -0.470$. This estimate is low due to both the relatively high share of land of single-family homes in the Zurich area and the relatively low elasticity of substitution.

7.3 Conclusions of Part III

The last decade has seen a worldwide concern for the impact of sprawling cities on the availability of open spaces and, in general, on the sustainability of urban development. On the other hand, many urban dwellers have enjoyed access to better (and larger) houses. For example, in the Canton of Zurich the per capita dwelling size has increased by 2.3 square meters, i.e. by 5.1%, in the relatively short span between 2000 and 2006. Raising urban density is often advocated as a way to satisfy the increasing demand for new housing units (Salvi, 2007). The capacity of the housing market to react to exogenous changes in the supply of land available for development is central to this debate. One of the contributions of urban economics is the careful quantification of the extent to which land is substituted with capital when the relative price of land changes. In our empirical work we've show that, for the region of Zurich, the magnitude of this substitution is relatively low.

Chapter 8

Conclusions

This dissertation has highlighted the use of property prices as a way of revealing the value individuals put on environmental amenities and on the characteristics of the built environment. It has dealt with themes common to both urban, real estate and environmental economics. The practical importance of the hedonic method in the Swiss retail banking and real estate industry is already well-established and has been documented elsewhere (Salvi and Schellenbauer, 2004). The settlement of the litigations related to the aircraft noise at Zurich Airport on the basis of the hedonic model presented in Part I is an encouraging broadening of its scope. The range of the possible applications of the hedonic method could be further extended to important issues in nonmarket valuation, expropriation and natural resource damage litigation. As so often in applied economics, the availability of new data sources, e.g. geocoded data and property transaction data, will continue to have a major impact on this area. Our results suggest that an extra Swiss franc may be better used in improving the data rather than in refining the spatial econometrics.

On a more general level, the estimation of underlying behavioral equations – as attempted in the second part of the dissertation – has been less common in the literature, but recently significant progress has been made here as well. It is thus fair to expect that we will see further advances in both theory and applications. The new nonparametric techniques inspired by related work in the Industrial Organization are a promising area for research. They allow the amenities to enter the models in a flexible and more realistic way as they account for the heterogeneity of consumers. Many important urban phenomena, as, e.g., the segregation and sorting of households in cities or the fiscal competition among jurisdictions, are related to the heterogeneity of preferences and income.

Urban and real estate economics was pioneered in the 1960s. It focuses on the spatial relationships to understand the economic motivations underlying the formation, functioning, and development of the built environment. Its strong ties to formal economic theory and the extensive use of quantitative methods still distinguishes modern urban economics from its closest substitutes. This attachment to theory and measurement provides urban economics with discipline and with a clear structure. Other disciplines – for example, urban planning – have a stronger normative approach and do not rely much on formal analysis and statistical testing. Yet, in practice they arguably have a higher impact on day-to-day decisions of the stakeholders. Indeed, the self-imposed hurdles of economics are sometimes high. This work was my modest attempt at surmounting some of them.

Bibliography

Ackerberg, Daniel, Lanier Benkard, Steven Barry and Ariel Pakes (2005), "Econometric Tools for Analyzing Market Outcomes", Working Paper.

Anselin, Luc (2003), "Spatial Externalities, Spatial Multipliers, And Spatial Econometrics", *International Regional Science Review*, 26 (2), pp. 153–166.

Awan, Kazim, John C Odling-Smee and Christine M E Whitehead (1982), "Household Attributes and the Demand for Private Rental Housing", *Economica*, 49 (194), pp. 183–200.

Bajari, Patrick and C. Lanier Benkard (2005), "Demand Estimation with Heterogeneous Consumers and Unobserved Product Characteristics: A Hedonic Approach", *Journal of Political Economy*, 113 (6), pp. 1239–1276.

Bajari, Patrick and Mattew H. Kahn (2002), "Estimating Housing Demand with an Application to Explaining Racial Segregation in Cities", Working Paper.

Bajari, Patrick and Mattew H. Kahn (2004), "The Private and Social Costs of Urban Sprawl: The Lot Size Versus Commuting Tradeoff", Working Paper.

Baranzini, Andrea and José V. Ramirez (2005), "Paying for Quietness: The Impact of Noise on Geneva Rents", *Urban Studies*, 42 (4), pp. 633–646.

Baranzini, Andrea, José Ramirez, Caroline Schaerer and Philippe

Thalmann (eds.) (2008), *Hedonic Model in Housing Markets*, Springer, Berlin.

Bartik, Timothy J. (1987), "The Estimation of Demand Parameters in Hedonic Price Models", *Journal of Political Economy*, 95 (1), pp. 81–88.

Bayer, Patrick, Fernando Ferreira and Robert McMillan (2007), *A Unified Framework for Measuring Preferences for Schools and Neighborhoods*, NBER Working Papers 13236, National Bureau of Economic Research, Inc.

Bayer, Patrick, McMillan and Kim Ruben (2002), "The Causes and Consequences of Residential Segregation: An Equilibrium Analysis of Neighborhood Sorting", Working Paper.

Berry, Steven, James Levinsohn and Ariel Pakes (1995), "Automobile Prices in Market Equilibrium", *Econometrica*, 63 (4), pp. 841–890.

Bishop, Kelly and Christopher Timmins (2008), "Simple, Consistent Estimation of the Marginal Willingness to Pay Function: Recovering Rosen's Second Step without Instrumental Variables", Working Paper.

Bockstael, Nancy E. and Kenneth E. McConnell (2007), *Environmental and Resource Valuation with Revealed Preferences: A Theoretical Guide to Empirical Models*, Springer, Dordrecht, The Netherlands.

Boyle, Melissa A. and Katherine A. Kiel (2001), "A Survey of House Price Hedonic Studies of the Impact of Environmental Externalities", *Journal of Real Estate Literature*, 9 (2), pp. 117–144.

Brown, James and Harvey Rosen (1983), "On the Estimation of Structural Hedonic Price Models", *Econometrica*, 50, pp. 765–769.

Brueckner, Jan K., Jacques-Francois Thisse and Yves Zenou (1999), "Why is central Paris rich and downtown Detroit poor?: An amenity-based theory", *European Economic Review*, 43 (1), pp. 91–107.

Cahuc, Pierre and André Zylberberg (2004), *Labour Economics*, MIT Press, Boston.

Clapp, John M. (1980), "The elasticity of substitution for land: The effects of measurement errors", *Journal of Urban Economics*, 8 (2), pp. 255–263.

Cliff, Andy D. and John Keith Ord (1972), "Testing for Spatial Autocorrelation Among Regression Residuals", *Geographic Analysis*, 4, pp. 267–284.

Cohen, Jeffrey P. and Cletus C. Coughlin (2006), "Spatial Hedonic Models of Airport Noise, Proximity, and Housing Prices", Working Paper.

Cressie, Noel A. (1993), *Statistics for Spatial Data*, John Wiley and Sons, New York.

Dowall, David E. and Alan P. Treffeisen (1991), "Spatial transformation in cities of the developing world : Multinucleation and land-capital substitution in Bogota, Colombia", *Regional Science and Urban Economics*, 21 (2), pp. 201–224.

Dubin, Robin A., R. Kelley Pace and Thomas G. Thibodeau (1999), "Spatial Autoregression Techniques for Real Estate Data", *Journal of Real Estate Literature*, 7 (1), pp. 79–95.

Ekeland, Ivar, James J. Heckman and Lars Nesheim (2002), "Identification and Estimation of Hedonic Models", Working Paper.

Epple, Dennis (1987), "Hedonic Prices and Implicit Markets: Estimating Demand and Supply Functions for Differentiated Products", *Journal of Political Economy*, 95 (1), pp. 71–80.

Epple, Dennis, Brett Gordon and Holger Sieg (2006), *A Semi-Nonparametric Approach to Estimating ProductionFunctions When Output Prices are Unobserved*, 2006 Meeting Papers 105, Society for Economic Dynamics.

Erol, Isil and Alper Guzel (2006), "The Elasticity Of Capital-land Substitution In The Housing Construction Sector Of A Rapidly Urbanized City: Evidence From Turkey", *Review Of Urban and Regional Development Studies*, 18, pp. 85–101.

Ferreira, Fernando V. (2004), "You Can take it with You: Proposition 13 Tax Benefits, Residential Mobility, and Willingness to Pay for Housing Amenities", Wharton School, University of Pennsylvania.

Florax, Raymond J. G. M., Hendrik Folmer and Sergio J. Rey (2003), "Specification searches in spatial econometrics: the relevance of Hendry's methodology", *Regional Science and Urban Economics*, 33 (5), pp. 557–579.

Flughafen Zürich AG (2008), "Statistic Report", Zürich.

Glaeser, Edward L. and Joseph Gyourko (2003), "The Impact of Building Restrictions on Housing Affordabilty", *FRBNY Economic Policy Review*, 9 (2), pp. 21–39.

Glaeser, Edward L., Joseph Gyourko and Raven Saks (2005), "Why Is Manhattan So Expensive? Regulation and the Rise in Housing Prices", *The Journal of Law and Economics*, 48, pp. 331–369.

Glaeser, Edward L., Matthew E. Kahn and Jordan Rappaport (2000), *Why Do the Poor Live in Cities?*, NBER Working Papers 7636, National Bureau of Economic Research, Inc.

Hastie, Trevor and Robert Tibshirani (1990), *General Additive Models*, Chapman and Hall, New York.

Heckman, James J., Rosa Matzkin and Lars Nesheim (2003a), *Simulation and Estimation of Hedonic Models*, IZA Discussion Papers 843, Institute for the Study of Labor (IZA).

Heckman, James J., Rosa Matzkin and Lars Nesheim (2003b), "Simulation and Estimation of Nonadditive Hedonic Models", NBER Working Paper No. 9895.

Jackson, Jerry R., Ruth C. Johnson and David L. Kaserman (1984), "The Measurement of Land Prices and the Elasticity of Substitution in Housing Production", *Journal of Urban Economics*, 16 (1), pp. 1–12.

Jones, H. F. (1997), *Validity of Leq as a Predictor of the Impact of Aircraft Noise on People*, Tech. rep., Heathrow Association for the Control of Aircraft Noise.

Kaufmann, Daniel and John M. Quigley (1987), "The Consumption Benefits of Investment in Infrastructure : The Evaluation of Sites-And-Services Programs in Underdeveloped Countries", *Journal of Development Economics*, 25 (2), pp. 263–284.

Keane, Michael P. (2003), "Comment on "Simulation and Estimation of Hedonic Models" by Heckman, Matzkin and Nesheim", Working Paper.

Kelejian, Harry H. and Ingmar R. Prucha (1999), "A Generalized Moments Estimator for the Autoregressive Parameter in a Spatial Model", *International Economic Review*, 40, pp. 509–533.

Loader, Catherine (1999), *Local Regression and Likelihood*, Springer, New York.

Malpezzi, Stephen and Duncan Maclennan (2001), "The Long-Run Price Elasticity of Supply of New Residential Construction in the United States and the United Kingdom", *Journal of Housing Economics*, 10 (3), pp. 278–306.

Matzkin, Rosa (2003), "Nonparametric Estimation of Nonadditive Random Functions", *Econometrica*, 71 (5), pp. 1339–1375.

McDonald, John F. (1981), "Capital-land substitution in urban housing: A survey of empirical estimates", *Journal of Urban Economics*, 9 (2), pp. 190–211.

McFadden, Daniel (1977), *Modelling the Choice of Residential Location*, Cowles Foundation Discussion Papers 477, Cowles Foundation, Yale University.

McMillen, Daniel P. (2004), "Airport Expansions and Property Values", *Journal of Urban Economic*, 55 (3), pp. 627–640.

Navrud, Ståle (2002), *The State-Of-The-Art on Economic Valuation of Noise. Final Report to EC/DG Environment*, Tech. rep.

Nelson, Jan P. (2003), "Meta-Analysis of Airport Noise and Hedonic Property Values: Problems and Prospects", *Journal of Transport Economics and Policy*.

Nelson, Jon P. (2008), "Hedonic Property Value Studies of Transportation Noise: Aircraft and Road Traffic", in: Andrea Baranzini, José Ramirez, Caroline Schaerer and Philippe Thalmann (eds.) *Hedonic Model in Housing Markets*, Springer.

O'Flaherty, Brendan (2003), "Commentary to Glaeser and Gyourko", *FRBNY Economic Policy Review*, 9 (2), pp. 41–43.

Pace, R. Kelley and Otis W. Gilley (1998), "Generalizing the OLS and Grid Estimators", *Real Estate Economics*, 26, pp. 331–347.

Palmquist, Raymond B. (2006), *Property Value Models*, vol. 2 of *Handbook of Environmental Economics*, chap. 16, pp. 763–819, Elsevier, Amsterdam.

R Development Core Team (2006), *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.

Revankar, Nagesh S (1971), "A Class of Variable Elasticity of Substitution Production Functions", *Econometrica*, 39 (1), pp. 61–71.

Rosen, Sherwin (1974), "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition", *Journal of Political Economy*, 82, pp. 34–55.

Salvi, Marco (2001), "Einfluss des Verkehrslärms auf die Preise von Einfamilienhäusern im Kanton Zürich", in: *Externe Kosten des Verkehrs: Hedonic Pricing Analyse*, UVEK.

SALVI, MARCO (2007), "Vom Nutzen der Nähe – Urbane Dichte und städtisches Wachstum", in: Vittorio Magnago Lampugnani, Thomas K. Keller and Benjamin Buser (eds.) *Städtische Dichte*, NZZ Libro, Zürich.

SALVI, MARCO and PATRIK SCHELLENBAUER (2004), *Preise, Mieten, Renditen: Der Immobilienmarkt transparent gemacht*, Zürcher Kantonalbank, Zürich.

SCHIPPER, YOUDI, PETER NIJKAMP and PIET RIETVELD (1998), "Why Do Aircraft Noise Estimates Differ? A Meta-Analysis", *Journal of Air Transportation Management*, 4, pp. 117–124.

SCHWEIZERISCHES BUNDESGERICHT (2008), "Enteignung nachbarrechtlicher Abwehrbefugnisse infolge Fluglärms sowie von Abwehrrechten gegen den direkten Überflug ausgehend vom Landesflughafen Zürich", BGE 1E.15/2007.

SHEPPARD, STEPHEN (1999), *Hedonic Analysis of Housing Markets*, vol. 3, chap. 41, pp. 1595–1636, North-Holland, Amsterdam.

SIRMANS, C. F., JAMES B. KAU and CHENG F. LEE (1979), "The elasticity of substitution in urban housing production: A VES approach", *Journal of Urban Economics*, 6 (4), pp. 407–415.

STATISTISCHES AMT DES KANTONS ZÜRICH (2004), "Bodenpreisstatistik", Zürich.

THOMANN, GEORG, RUDOLF BÜTIKOFER and WALTER KREBS (2004), *FLULA2: Ein Verfahren zur Berechnung und Darstellung der Fluglärmbelastung*, Tech. rep., Swiss Federal Laboratories for Materials Testing and Research.

THORSNES, PAUL (1997), "Consistent Estimates of the Elasticity of Substitution between Land and Non-Land Inputs in the Production of Housing", *Journal of Urban Economics*, 42 (1), pp. 98–108.

TINBERGEN, JAN (1956), "On the Distribution of Income", *Weltwirtschaftliches Archiv*, 77, pp. 155–173.

van Praag, Bernard M. S. and Barbara E. Baarsma (2005), "Using Happiness Surveys to Value Intangibles: The Case of Airport Noise", *Economic Journal*, 115 (500), pp. 224–246.

Waltert, Fabian and Felix Schläpfer (2007), "The Role of Landscape Amenities in Regional Development: A Survey of Migration, Regional Economic and Hedonic Pricing Studies", Working Paper.

Waugh, Frederick V. (1928), "Quality Factors Influencing Vegetable Prices", *Journal of Farm Economics*, 10, pp. 185–96.

Wheaton, William C (1977), "Income and Urban Residence: An Analysis of Consumer Demand for Location", *American Economic Review*, 67 (4), pp. 620–31.

Wirth, Katja, Mark Brink and Christoph Schierz (2006), *Lärmstudie 2000. Schlussbericht der 2. Befragungsstudie vom August 2003*, Tech. rep., ETH Zürich, Zentrum für Organisations- und Arbeitswissenschaften.

Wooldridge, Jeffrey M. (2002), *Econometric analysis of cross section and panel data*, The MIT Press, Cambridge, MA.

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"Spatial Estimation of the Impact of Airport Noise on Residential Housing Prices", *Swiss Journal of Economics and Statistics*, forthcoming.

Book contributions

"Die Baugenossenschaften in der Stadt der Ökonomen" in *Wohnen morgen. Standortbestimmung und Perspektiven des gemeinnützigen Wohnungsbaus*, 2008, Zürich: NZZ Libro (with Patrik Schellenbauer).

"Wertvoller Boden. Die Funktionsweise des Bodenmarktes im Kanton Zürich", 2008, Zürich: Zürcher Kantonalbank.

“Vom Nutzen der Nähe – Urbane Dichte und städtisches Wachstum”, in *Städtische Dichte*, 2007, Zürich: NZZ Libro.

“Preise, Mieten, Renditen: der Immobilienmarkt transparent gemacht”, 2004, Zürich: Zürcher Kantonalbank.

“Einfluss des Verkehrslärms auf die Preise von Einfamilienhäusern im Kanton Zürich”, in *Externe Kosten des Verkehrs: Hedonic Pricing Analyse*, 2001, Bern: UVEK.

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